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DYNAMIC CHARACTERISTICS OF SEISMIC WAVES DURING UNDERGROUND EXPLOSIONS

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О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

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DYNAMIC CHARACTERISTICS OF SEISMIC WAVES DURING UNDERGROUND EXPLOSIONS

B. G. Rulev

When establishing the dynamic characteristics of seismic waves during underground explosions special attention has been allotted to the investigation of the origin and conditions of excitation of seismic waves, and also to the connection of the parameters of the origin with the dynamic characteristics of the seismic waves. The obtained seismograms show that the seismic effect must be estimated separately according to every wave mode, since during specific explosions at different distances any wave can be the maximum in intensity. This is connected with the fact that the dependence of particle speed (criterion for the estimation of the danger to the structures) on the weight of charge and on the distance is different for every wave mode. This is especially important during the investigation of complex explosions (short-delay, distributed, etc.), where, depending on the conditions of the explosion, every wave can change its parameters to a different degree.

The investigations showed that it is not possible to describe the intensity of seismic waves during explosions by one dependence, since with a change in the distance the maximum

speed can be recorded successively in two-three waves. During the explosion of another force on the same site, the maximum speeds can already be a part of one-two waves.

The description of the maximum intensities by one by dependence (as this was made earlier) is the obstruction to an increase in the accuracy of the prediction of the expected speeds or displacement into waves, and furthermore, provides an inaccurate basis for research on more complex explosions (short-delay, distributed, etc.).

The breakdown of the entire profile of observations on specified ranges of distances is unjustified; within each range there should be a set of laws. Measurements show that the boundaries of the transition of the maximum intensities of one wave to another (and consequently, a change in the law) vary quite arbitrarily, depending on the weight of the charge, depth of its placement and the structure of the site. With an increase in weight only of the charge detonated at one and the same site, some waves can not be considered at all. The sole physically justified boundary when dividing the ranges based on distance can it be considered the zone of transition from the inelastic vibrations to the elastic ones. But the latter is the boundary of the focus range from which strictly the seismic vibrations (waves) begin. It is possible to add to this that in certain cases considerable disturbances from the reflected waves are observed. The boundary of reflection in this case can be located at a very great depth, and therefore, it is frequently not considered in the examination of the geological structure of the investigated region or industrial site.

In the process of measuring the seismic waves a special procedure for the observations was perfected making it possible to encompass the entire range of tracking the waves of interest to us along with a sufficient degree of detail. For the test

conditions data were required for finding the largest possible range of distances with the minimum number of instruments. As a rule, during every explosion established a longitudinal profile with the spacing between the instruments increasing with distance by the geometric progression $\Delta r_{n+1} = (1.3\text{-}1.6)\Delta r_n$. The assured correlation of the phases of the surface wave required in order that the spacing between the instruments would not exceed a specific value. The maximum distance Δr_{max} in this case depends on the value of the oscillatory period of the soil, the phase and group wave velocity. The elementary geometric structures give a value Δr_{max}, at which it is possible to confidently trace a similar phase of the surfaces of the wave at adjacent points:

$$\Delta r_{max} = \frac{v_0 v_c}{v_0 - v_c} T, \text{ m},$$

where T - period of the surface wave, s; v_0 and v_c - phase and group velocities, m/s.

This nonuniform instrumentation agrees with the nature of a change in the wave amplitudes with distance, which, as a rule, are approximated by exponential functions.

For the observations broadband equipment was used with a frequency band 1-100 Hz making it possible to record the displacement of the soil from 1 μ to 100 mm. For the study of the focus zone where large displacements are observed, special seismic sensors were devised [1]. The large amount of simultaneously utilized equipment resulted in a search for simpler methods for determining the instrument constant and construction of the frequency characteristics. This position was complicated by the fact that during the observations it was necessary to change the seismic sensor or galvanometer to a pair (channel) and frequently change the shunt registers. This eliminated data sheets for the seismic sensor channels , i.e., the galvanometer; therefore

the initial calculated values were the parameters of the seismic sensor and the galvanometer. Thus, during analogous observations the method of calibrating the equipment on platform vibrator was eliminated, and the calculated method of determining the frequency characteristics was the basic means. However, in the predominant majority of cases the periods of the observed waves fell on the tabular part of the frequency characteristic; therefore, the calculation of the increase in the channel was considerably simplified. It was sufficient to determine the nominal increase in the parameters of the seismic sensor and galvanometer.

Focus Range

During the first detailed seismic investigations of large explosions in clay [2] a representation was obtained about the nature of the wave picture and the types of most intense waves for media, for a structure, close to a half-space (without sharp boundaries and with an insignificant velocity gradient). The wave picture for the different kinds of soil is qualitatively similar which is confirmed by experimental explosions at sites consisting of other soils. Three wave modes were revealed commensurable in intensities, which in turn, depending on the distance to the source and magnitude of the charge, are predominating with respect to amplitude: straight longitudinal wave p (refracted, if the medium is gradient), unidentified wave designated N, and Rayleigh's surface wave R. Wave N has the symbol of waves p and R.

Connected with the reasons for the formation of these waves is the representation about the nature of the origin of the seismic waves during explosions near a floating surface [2]. Typical seismograms of the motion of the soil in the epicentral zone in the case where the soil was not loaded on the surface, are given in Fig. 1. Distinctly visible are two maximums, which can be formed only from the waves radiated by two different sources.

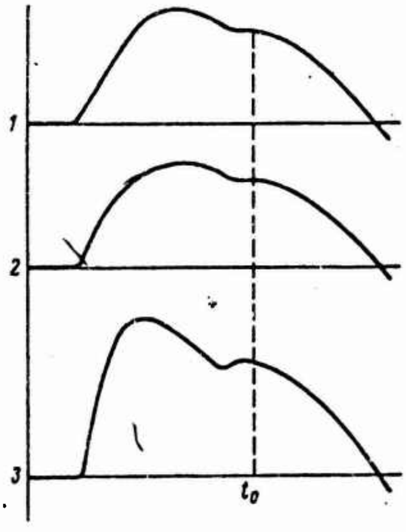

Fig. 1. Typical seismograms of the motion of the soil in the epicentral zone: 1 - at the epicenter; 2 - r = 0.5 h_3; 3 - r = h_3.

The disagreement with previous representations about the origin of the explosion just as with the center of expansion, which radiates into space only as a longitudinal wave, forces one to turn to the processes which take place in the area surrounding the charge after the detonation of the explosives.

With the placement of the charge at a great distance from the floating surface, when one excludes its effect on the stress field during the process of the formation of the elastic wave, the origin can be schematized as the center of expansion. In this case only the spherically symmetrical longitudinal waves are radiated. On the strength of this simplest case, one can proceed to the more complex scheme of the origin of the explosion.

Construction of the diagram for the origin as the dual source of waves during an explosion near the floating surface is based on research for the investigation of the mechanical effect of an explosion in a surrounding massif of solid rock[1].

[1]See the articles by V. B. Lebedev, et al., V. N. Rodionov, et al. in the present collection.

The detonation of the charge transfers the energy of the explosives into potential energy of the gases. Under the effect of gas pressure in the surrounding medium an impact wave is formed which puts the medium in motion. After the full cessation of the motion of the medium near the origin of the explosion, a spherical cavity remains. The volume of the cavity for the specified medium is proportional to the quantity of liberated energy. With the same energy of the explosives, the volume of the cavity strongly depends on the strength properties of the medium. So, for the entire array of rocks, from the softest to the strongest, the volume of the cavity can change by two orders. This value can serve as the unique strength characteristic of the medium. In industry, the so-called index of leakage II - the volumetric ratio of the cavity to the weight of the charge is utilized. This index, depending on the properties of the rock in which an explosion is set off, changes from unity to hundreds.

The spherical cavity (Fig. 2) is surrounded by disintegrated or fractured rock. This zone of disturbed rock is converted into a zone of radial fracture where the failures originate from the circular tensile stresses. Beyond the zone of fracture follows an elastic zone with a radius $r_{\text{упр}}$, where there are no disturbances of the massif as an entity.

In the works of V. N. Rodionov, et al. formulas are given for calculating the size of the radii of the different zones based on the strength properties of the medium - such, as maximum stress on crushing σ^*, density ρ, the velocity of the propagation of the longitudinal waves v_p, Poisson ratio ν, the plastic limit $\sigma_{\text{пл}}$ etc. If at first one considers the elastic range as the radiating boundary or, at least, the value characterizing the range of the radiating waves, then the value of these formulas is indisputable for the study of the dynamic characteristics of seismic waves.

The change in the state of the medium occurs as a result of the passage of shock, compression and longitudinal waves as

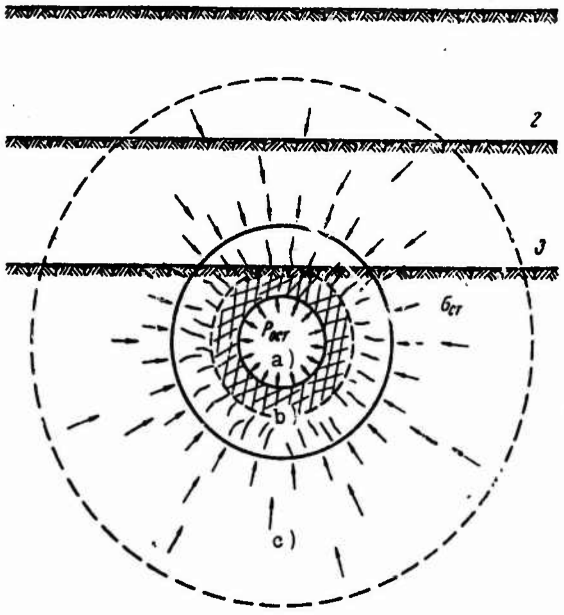

Fig. 2. Diagram of the formation of different zones after detonating an underground explosion in the medium: a) cavity; b) zone of failure; c) elastic stress zone: 1, 2, 3 - various positions of the floating surface relative to the origin of the explosion.

successively the one and same environmental disturbance, depending on the pressure at the front. The described picture represents the source of the type of center of expansion which radiates spherical longitudinal wave. Let us recall that this source is feasible in infinite space in a uniform isotropic solid medium, and the explosion itself is called camouflet.

As a result of the explosion the formed spherical cavity is filled with expanded gases which have sufficiently high pressure p_{OCT} and potential energy E, capable of producing additional work. The parameters of the gases in the cavity depend on the dimensions of the charge chamber and cavity, and also on the weight of the detonated explosives. By knowing the

index of leakage for the specific medium, it is possible to evaluate the values $p_{ост}$ and E. By applying the adiabatic curve of the expansion of the products of explosion, according to Jones [3], and the indices of leakage for granite, $\Pi = 3\ m^3/t$ and for loess deposits, $\Pi = 350\ m^3/t$, we will find that $p_{ост} = 2000$ and 3 kgf/cm^2 respectively, $E_{ост}/E_{общ} = 57$ and 10%, respectively.

The cavity, according to the data of V. N. Rodionov, et al., is formed in essence, because the volume of rock is excluded from the elastic zone, and also as a result of packing in the zone of fragmentation (approximately one fourth of the volume of the cavity). For porous rocks - such, as loess deposits, an additional increase in the volume causes the collapse of the pores. Thus, after the termination of cavity formation and radiation of the longitudinal wave, gases remain with considerable pressure, which are restrained by the stresses in the elastic zone $\sigma_{ст}$. With a full camouflet when any effect of the floating surface is excluded, a decrease in the stresses in the elastic zone occurs or this may be due to gas escape from the cavity through fissures or as a result of the rheological properties of the substance making up the medium; for example, the property of creep. However, these processes last over an indefinite long time in comparison with the time of the radiation of elastic waves, and therefore, with respect to the examined phenomena, they are not of interest to us.

The stressed elastic zone which holds the residual gas pressure in the cavity, occupies a specific volume around the origin of the explosion. In infinite half-space both the picture of failures and of the stress field in the elastic zone, will be spherically symmetrical.

During an explosion near floating surface the process of cavitation will be, obviously, different. The model experiments

carried out in plastic medium of the plasticene type, display the spherical symmetry of the cavities, as well as the field of displacements; consequently stress fields, also convert into axisymmetrical ones. The processes in the soil which surrounds the cavity, are prolonged. In the work by V. B. Lebedev, et al. under laboratory conditions the nature of the motion of the medium which surrounds the cavity was measured. From this work it is evident that during the first stage of the development of an explosion, the process of cavitation and of the elastic wave, is analogous to the phenomena which take place during underground explosions.

The pressure in the cavity, which cannot be retained by part of the elastic stress field, located at the top (see Fig. 2, position 2, 3), causes motion of the surrounding cavity of the medium. In this case the points which are located higher than the center of the charge, move to the floating surface also along the horizontal from the burst center, continuing the motion of the first stage in the development of the cavity. The points lying lower than the center, move downward and towards the burst center, i.e., in comparison with the first stage, they sharply change direction. The duration of this process is several times longer than the time of development of the first stage. Thus, depending on the placement depth of the charge, a partial or full discharging of the stressed state of the medium occurs. In the case of full camouflet (see Fig. 2, position 1) this discharging lasts for an indefinite long time.

The motion of the soil in the adjacent zone observed during model experiments, qualitatively agrees with the observations during explosions under real conditions. The description of the nature of the motion of the soil based on observations in a mine, is given in N. V. Kuz'mina's work[1]. Under real conditions,

[1]See the article "Vibrations of the soil during explosions according to observations within the medium and on the floating surface" in the present collection.

just as in model experiments, the more intense motion of the medium near floating surface (higher than the placement of the charge) is noted and also a reverse motion of the medium during the second stage in the development of the cavity at points lying lower than the charge.

During the second stage the spherical cavity which is formed at the first point in time, is converted in an elliptical one, and with a closely arranged floating surface an ejection of soil can occur which is located above charge.

The motion of soil during the second stage in the development of a cavity can cause the formation of secondary waves with large periods, since at this point the process takes place more slowly. The elastic strains $\sigma_{\text{ст}}$ containing the residual pressure in the cavity, depending on the proximity of the floating surface are not removed completely. In proportion to the distance of the floating surface from the center of the charge (see Fig. 2, position 2) an increasingly less portion $\sigma_{\text{ст}}$ will be removed. As a result of this the motion amplitude at the epicenter and the intensity of the secondary waves should decrease with an increase in depth. When the floating surface is at a distance approximately equal to the radius of destruction and closer (see Fig. 2, position 3), the stresses in the elastic zone completely are removed, but their maximum value decreases in proportion to the proximity of the floating surface to the center of the charge, since a part of the energy of the gases is spent in lifting the disrupted soil. During a contact explosion (on a floating surface) there will be also some final (relatively small) value of elastic strains and secondary waves can appear. Thus, the intensity of the movement of the soil at the second stage has, obviously, a maximum at depth $h_3 \approx r_{\text{упр}}$ and, as a consequence of this, approximately at this depth it is possible to expect the maximum of intensity of the secondary waves.

It is necessary to focus one's attention on an essential distinction in the reasons for the motion of the medium during the first and second stages in the development of cavities, which cause the different nature of the waves connected with these stages. This is important in setting up formulas and similarity criteria on the dynamic characteristics of these waves. During the first stage the movement of the particles of the medium both near and in the elastic zone is almost instantaneous, in comparison with the total time of motion; a specific fraction of the kinetic energy is obtained, i.e., the initial condition for the motion of the medium should be any final velocity or the almost instantly applied pressure. The second stage begins from the moment when the medium on the boundary of elastic zone has an initial displacement caused by stresses and by the specified supply of potential energy.

The recording of the soil vibrations was conducted on a profile, the nearest points of which fell in the zone of failures near the epicenter where residual deformations occurred. The termination of the profile was set in the zone of elastic oscillations. Thus, observations covered the zones of both inelastic and elastic deformations. According to observations curves of the amplitude and time parameters of oscillations were plotted depending on distance [4, 5]. The curves show that the amplitudes of the soil displacement in both the longitudinal and the surface waves in the near zone decrease with an increase in the distance from the charge, according to the law r^{-4}, but in the elastic zone they decrease according to the law r^{-1}-r^{-2}. The visible oscillatory periods in these waves in the near zone decrease according to the law r^{-1}, and in the elastic zone, they remain constant or begin to increase. In [6], it is shown that the particle displacement of the soil in epicenter zone is the consequence of their motion in the gravitational field because the kinetic energy obtained during the loading of the medium

at the moment of passage of the compression wave. The indicated phenomena and the laws governing the particle motion of the soil during an explosion near the floating surface when the placement depth of the charge is less than the radius of the zone of inelastic deformations, are observed at points lying higher than the hypocenter. At points lying below the hypocenter, and also in the case of an explosion in an unconfined medium, apparently, there will be other laws. In these cases the particle displacement will be considerably less as a result of the resistance of the surrounding medium.

For the calculation of structures the parameters of motion of the soil in the near zone are very rarely utilized, since explosions are usually not set off at such close distances. Furthermore it is possible, that the supplementary stresses in the structures will turn out to be more essential as a result of residual deformations in the soil. Therefore, great significance is attached to the estimations of the sizes of the zone of inelastic deformations which just as the size of the origin, are included in formulas for the calculation of the parameters of seismic waves. The recording of the amplitudes of the displacement and wave periods in the region of transition from the near zone to the elastic, and the establishment of the beginning of the elastic zone according to the point of inflection on the curves of the dependence of amplitudes and periods on the distance, are one of the methods of determining the size of the origin.

It is possible to make estimates of the stresses, tested in soils at a distance $r_{\text{упр}}$, and to compare them with maximum stresses upon rupture. For this the known relationship $\sigma_{rr} = \rho u v_p$ is applied. The values $r_{\text{упр}}$ for different soils determined by seismic methods, and the vibration velocity of the particles are given below. The vibration velocities of the particles are determined according to the longitudinal wave at a distance

$r = r_{упр}$. The observed data on the floating surface can be used, since wave p in the majority of cases emerges at right angles to the surface. Furthermore, there are virtually no data on the stresses in the soils upon rupture, interruption and only the order of magnitude is known. More specific is the comparison of the different soils between themselves and the comparison of the obtained maximum stresses upon rupture with the velocities of the longitudinal waves having values to a certain degree proportional to the strength characteristics of the soils.

Table 1 for the different soils gives a radius of the boundary of elastic zone $r_{упр}$ the particle speed in the longitudinal wave at this distance u, the velocity of propagation of the longitudinal waves with depth of explosion v_p and the density of the rocks ρ. Azimuth maximum stresses upon rupture are determined by the expression

$$\sigma_{\varphi\varphi} = \frac{\nu}{1-\nu}\sigma_{rr},$$

which is real for flat waves, but for estimations in spherical waves, it is necessary to consider that $\sigma_{rr} \approx \sigma_{\phi\phi}$. Relative deformations are calculated according to the ratio $\varepsilon = u/v_p$.

Estimates of the maximum stresses upon rupture given in Table 1, provide completely real values. For granite, values $\sigma_{\phi\phi}$ and v_p were underrated as a result of the fact that the explosions took place in an upper fissured zone. Maximum stresses $\sigma_{\phi\phi}$ agree sufficiently well with parameter ρv_p, which is the relative characteristic of the strength of the rock.

Based on this, the estimates first in the elastic zone during the first approximation can be considered as satisfactory. If the size of the origin is estimated by the zone of inelastic

Table 1.

(1) Порода	(2) $\dfrac{r_{упр}}{q^{\frac{1}{3}}}$	u, см/сек	v_p, м/сек	ρ, г/см³	$\sigma_{\phi\phi}$, кГ/см²	$\dfrac{\rho v_p^2}{10^6 \cdot \sigma_{\phi\phi}}$	$\dfrac{\varepsilon}{10^{-5}}$
(3) Лёссовидный суглинок	2,5	6,5	400—800	1,6	0,41—0,85	6,3—12,0	0,8—1,6
(4) Глина	7,0	8,0	700—1800	2,0	1,2—2,9	9—22	0,5—1,2
(5) Гранит	4,5	18,0	4300	2,7	21,0	17,6	0,4
(6) Мраморизованный известняк . . .	3,0	40,0	5200	2,7	57,0	9,5	0,8

KEY: (1) Rock or soil; (2) Elastic; (3) Loess-like loam; (4) Clay; (5) Granite; (6) Marble limestone.
DESIGNATIONS: см = cm; сек = s; г = g; кГ = kgf.

deformations, then value $r = r_{упр}$ amounts to an approximate radius of the focus zone. The relative deformations at this distance have approximately one order of magnitude ($\varepsilon \approx 10^{-5}$).

The Connection of Waves with the Nature of Origin

It was indicated above that in media, close in structure to a half-space, three predominating wave modes with respect to intensity can be observed. The kinematic and dynamic parameters of these waves were investigated during explosions in granite. A high-speed profile based on the longitudinal waves (Fig. 3), has a slight gradient near the surface.

A typical wave picture for two points is shown in Fig. 4. The basic oscillations of the soil occur in plane zx. Waves diverge from the origin located near the floating surface, since the arrivals and phases are outlined from the epicenter. The kinematic characteristics of the waves are very simple, and for an analysis it is sufficient to examine only their propagation rates.

The hodograph of the first arrivals (Fig. 5) is characterized by a continuous increase in the apparent velocity in

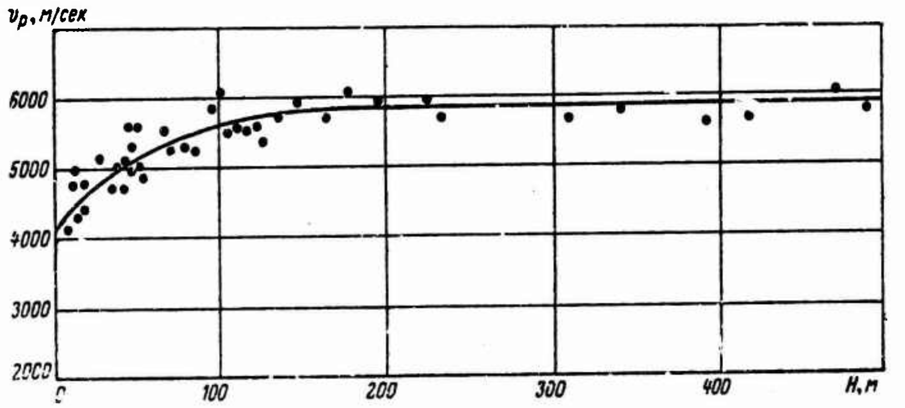

Fig. 3. High-speed profile based on the longitudinal waves at the site consisting of granites.

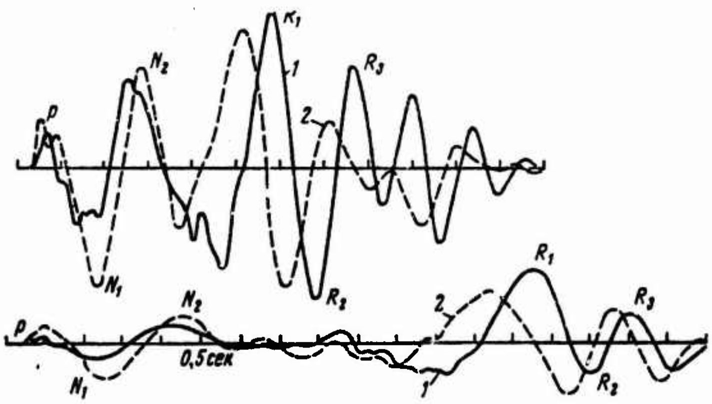

Fig. 4. Typical wave picture for two points during explosions in the media, close to a half-space: 1, 2 - vertical and horizontal (radial) components of motion; p, N, R - phases of the different waves.

proportion to the distance from the source. It is doubtful that we are dealing with a refracted wave and a gradient medium. It is necessary to note that the given high-speed profile (see Fig. 3) was built according to observations of the first arrivals of wave p of the examined explosions, without preliminary seismic survey.

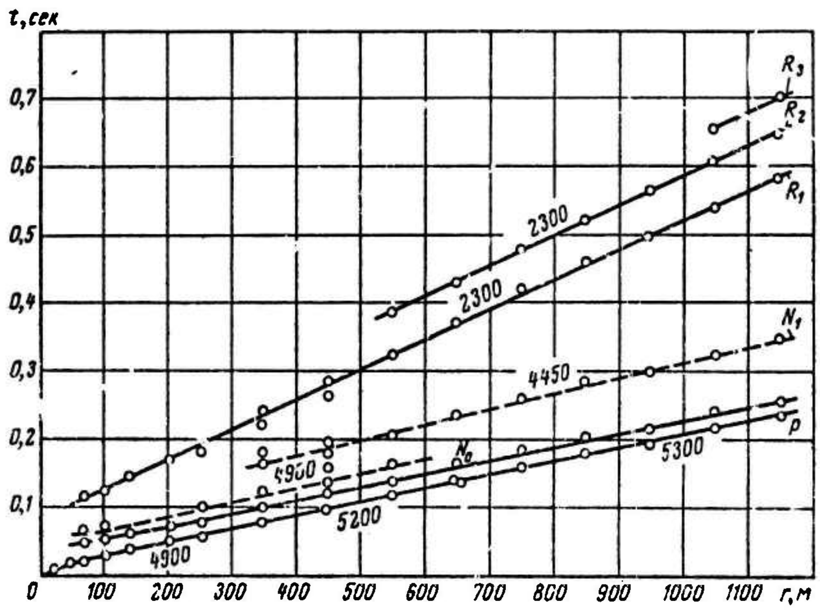

Fig. 5. Hodographs of waves during explosions in granite.

In real media near the the floating surface where industrial explosions are set off, in the overwhelming majority of cases a gradient structure occurs. In connection with this, for longitudinal waves which are emitted directly from the source, we will subsequently use the term "direct waves" regardless of whether or not they are actually straight lines (with a spherical wave front and with a constant velocity) or refracted ones. This is all the more sound since during explosions in different media (with different gradients) the essential distinction was not noticed in this important dynamic characteristic as the law of a change in the maximum amplitudes with distance. The decrease in the maximum amplitudes with distance is usually approximated as the exponential function in the form $a \approx r^{-n}$, where $n = 2 \pm 0.2$ (see Fig. 6, wave p).

For an explosion of a specific force the periods in a direct longitudinal wave are shorter than in other waves

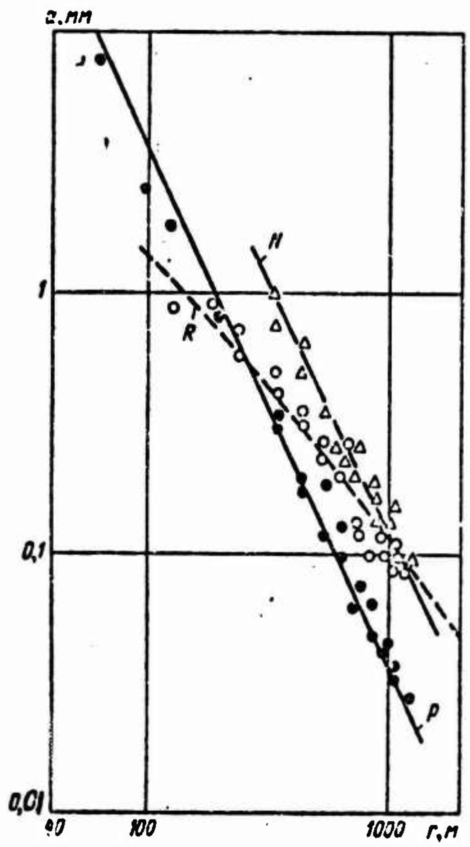

Fig. 6. Maximum wave amplitudes during an explosion in granite using a charge 10 t in weight.

(Fig. 7). If we trace the change in the value of the period with distance, then it is possible to note two segments: the initial one, where the period decreases, which is connected with nonlinear phenomena in the near zone, and the segment lying in the elastic zone where the period with distance does not change. If a tendency is noted toward an increase in the period with distance, then this is very insignificant.

Wave N in the first arrivals (see Fig. 4) has a considerably larger period, than the direct longitudinal wave; its value noticeably increasing with distance (see Fig. 7). Therefore, phases N_1, N_2, etc. have less speed, respectively (see Fig. 5). These effects are the consequence of wave dispersion N. However, the moments of the arrivals of this wave are the same as those of

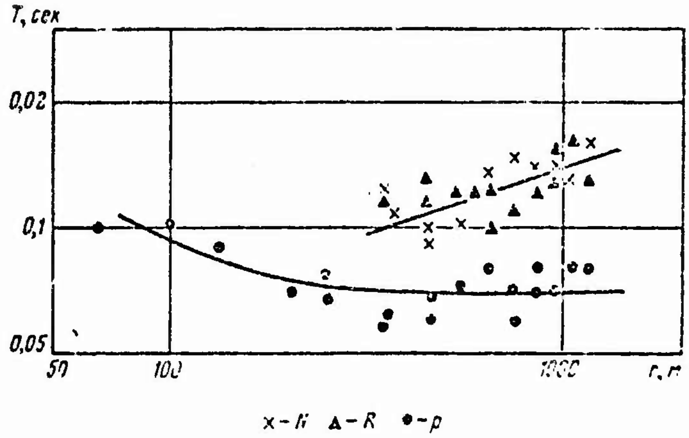

Fig. 7. Wave periods during an explosion in granite using a charge of 10 t.

wave p, although due to the imposition of the latter, they are difficult to isolate. Furthermore, wave N has the same degree of damping as wave p. It is clear that at this velocity and at this fading, not one wave cannot be propagated, besides the longitudinal one. Thus, the wave N, apparently, is a longitudinal wave.

For a comparison it is useful to examine certain properties of Rayleigh's surface wave, which are inherent in wave N. One of them - the visible period, is identical for both waves under study (see Fig. 7). The phase wave velocities R during a change in the period from 0.15 to 0.55 s increase from 2100 to 2500 m/s, i.e., a weak wave dispersion, completely natural for the medium with a small gradient, occurs. The change in the period, and consequently, the phase velocity as well, was observed during the explosions of different intensity, since period noticeably increases with a gain in the weight of the charge.

For wave R a change in the maximum displacement depending on distance is approximated by a curvilinear dependence at the log-log coordinates [4]. For small profiles the dependence of

the maximum displacement on distance can be substituted with an exponential function whose index is changed depending on distance. For the examined section of the profile n ≈ 1.3-1.5, i.e., it is less than for a direct longitudinal wave.

The values of the maximum displacement in the examined waves depending on the depth of the origin change differently. The corresponding curve for charges, 1 t in weight, is given in Fig. 8. Of all three waves with shallow depths, the intensity of the oscillations increases. This is for those depths at which the disturbance of the soil at the surface are noticeable, and therefore, the portion of energy which is transferred in the elastic waves changes. With a deeper placement of the charge, the intensity of wave p approaches a specified limit, whereupon it remains constant, if the medium is uniform.

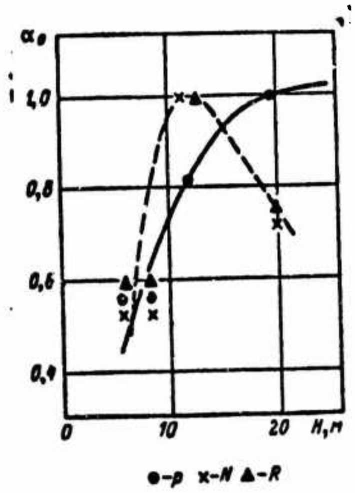

Fig. 8. Curve of the dependence of the relative maximum displacement on the depth of the origin based on an explosion in granite using a charge of 1 t.

The change in the intensity of waves N and R bears another nature. Upon achieving the maximum at a specified depth, the amplitudes of both waves begin to decrease and at a considerable submersion depth the displacements into waves N and R become incommensurably small by comparison with the displacement in wave p (on the recordings they are virtually absent). Let us

now examine the uniform properties of these waves. Waves p and N have just one velocity of propagation and one degree of damping at a distance n ≈ 2, i.e., the criteria which depend on the parameters of the medium along the passage of the waves and on the type of wave itself. Since the parameters of the medium are identical, just as the criteria of these waves are identical, waves p and N can be related to one type, namely, to the volumetric longitudinal waves. They are distinguished by the period and the effect of the placement depth of the charge on their intensity, i.e., by the properties which depend on the parameters of the source of the excitable waves. Specifically, according to these criteria which depend on the source, wave N has the general features of wave R.

By comparing these data, it is possible to present (qualitatively) the general nature of the origin of seismic waves during explosions near a floating surface. The origin is complex and has two sources of seismic waves, corresponding to two stages of motion of the soil in the near zone.

The second source is activated only if the charge is arranged near the floating surface (one can assume that even near any boundary with a sharp change in the properties of the medium). The second source propagates a long-period longitudinal wave N and a surface wave R. The first source propagates a short-range wave p at any placement depth of the charge. All these waves have considerable intensity. However, the possibility is not excluded as to the existence of other wave modes, as for example, Rayleigh's short-range wave (from the first source).

Thus, between the nature of the motion of the soil in the near zone and the wave picture during explosions near the floating surface, there is an analogy. This confirms the conformity between the intensities of the second stage of the motion of the soil in the focus zone and the secondary longitudinal wave.

Figure 9 shows seismograms of explosions produced at a different depth in one and the same hole. It is sufficiently and clearly evident that there is an extinction of long-period waves with deep placement of the charge, i.e., where the origin can be considered as the center of expansion, and also where a second stage in the motion of the soil should not exist.

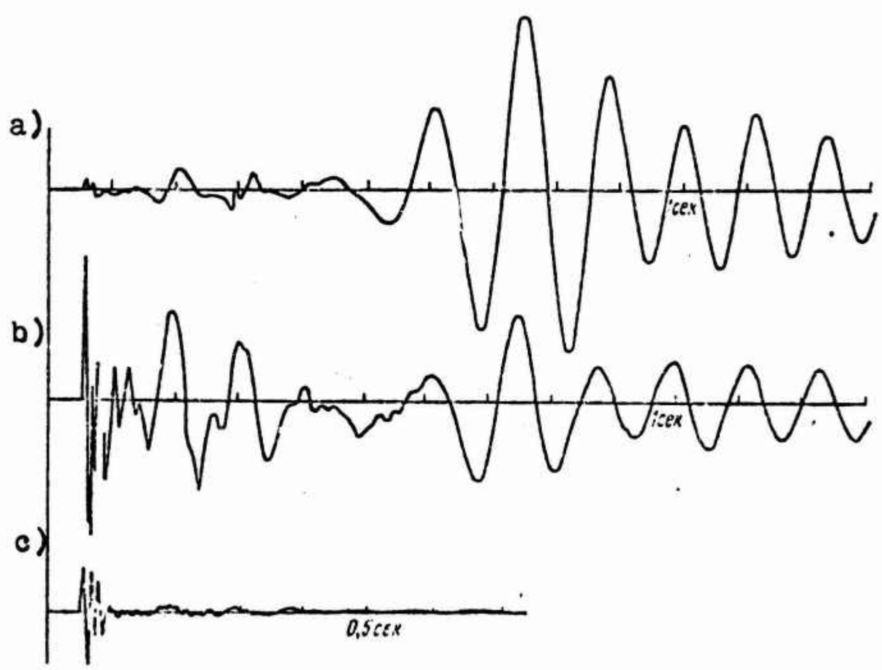

Fig. 9. Seismograms of the explosions of 3 kg charges in clays at depths: a) $h_3 = 0.5$ m; b) $h_3 = 10$ m; c) $h_3 = 20$ m.

The interfacies of the media strongly complicate the wave picture. In laminar media the appearance of supplementary waves is possible comparable in intensity with the three basic waves as for example, longitudinal waves reflected beyond the critical angle.

Let us examine a wave picture in which explosions of charges from 200 to 10,000 kg in weight, in loess-like loams is observed. At a depth 50 m, where in a loess-like loam there is an admixture of sand, and below, where there are inclusions of fine fragmental material, these seismic surveys indicate a sharp boundary (Fig. 10, dotted line). Supplementary information about the structure of the medium were obtained from hodographs plotted in the analysis of the basic explosions whose oscillograms were presented in Figs. 11 and 12. The hodograph of the first arrivals (Fig. 13) has a curvilinear form which can correspond to either alternating thin layers at increasing velocities, or to a medium which has a continuous increase in velocity. Assuming that the medium has a gradient structure the hodograph was processed for the first arrivals using the method of Chibisov [7], which makes it possible to determine a high-speed profile with any form of an increase in the velocity with depth (see Fig. 10, dots).

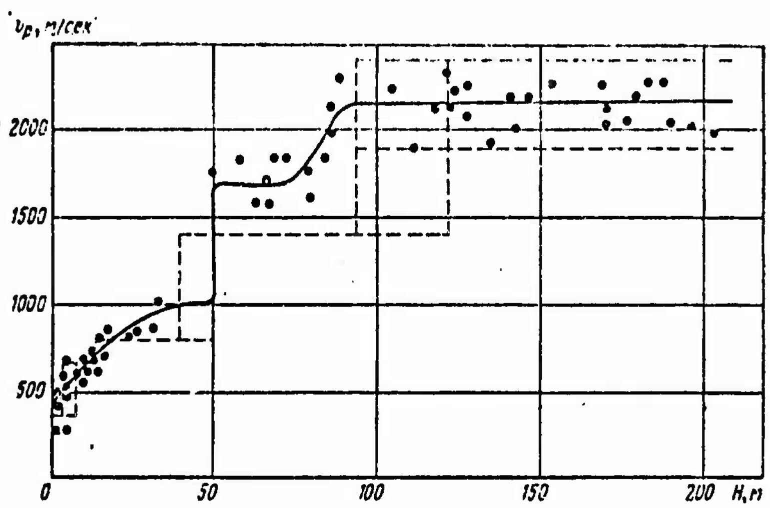

Fig. 10. High-speed profile based on the longitudinal waves which are formed during an explosion of charges from 20 to 10,000 kg in weight in loess-like loams.

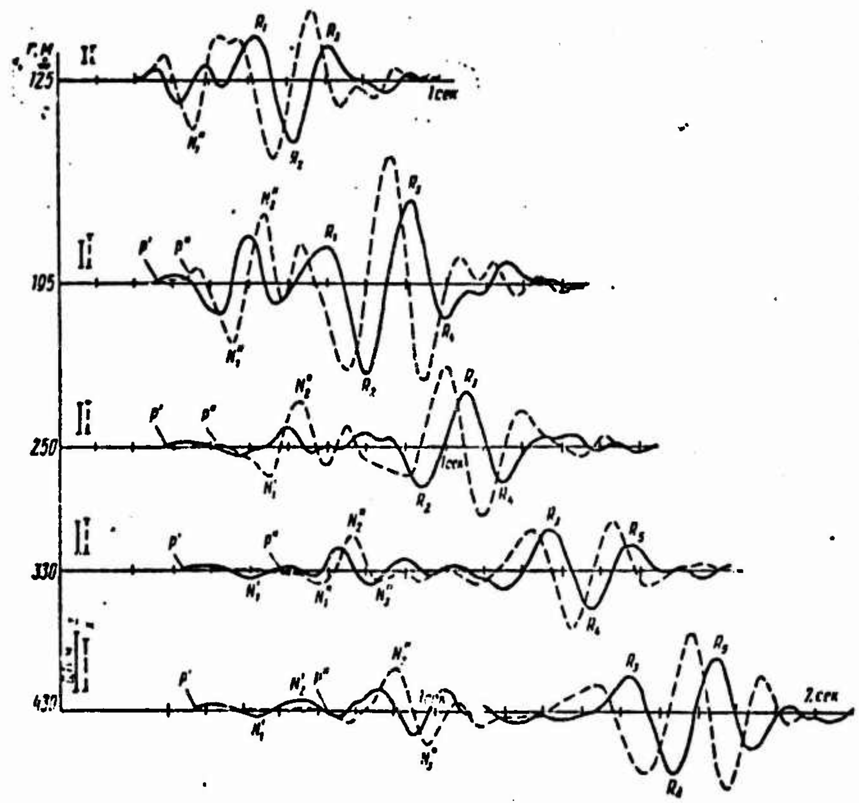

Fig. 11. Seisograms of the explosion of a 160 kg charge at a depth of 3.75 m; p, N, R - phases of the different waves.

This method does not provide information about depths on the order of 50 m due to the impossibility of obtaining kinematic data in the range of the loop of the hodograph, which testifies to the sharp exchange of the properties of the medium and the presence of the boundary which intensely reflects the wave. Thus, for the hodograph the first arrivals correspond to the refracted wave in the upper layer with a thickness of 50 m and the leading waves from the lower layers. A blurred boundary at a depth on the order of 30 m is noted.

The leading wave p' has insignificant intensity in comparison with the other wave modes. The maximum displacements in the leading wave decrease with distance according to the law $a \approx r^{-2}$

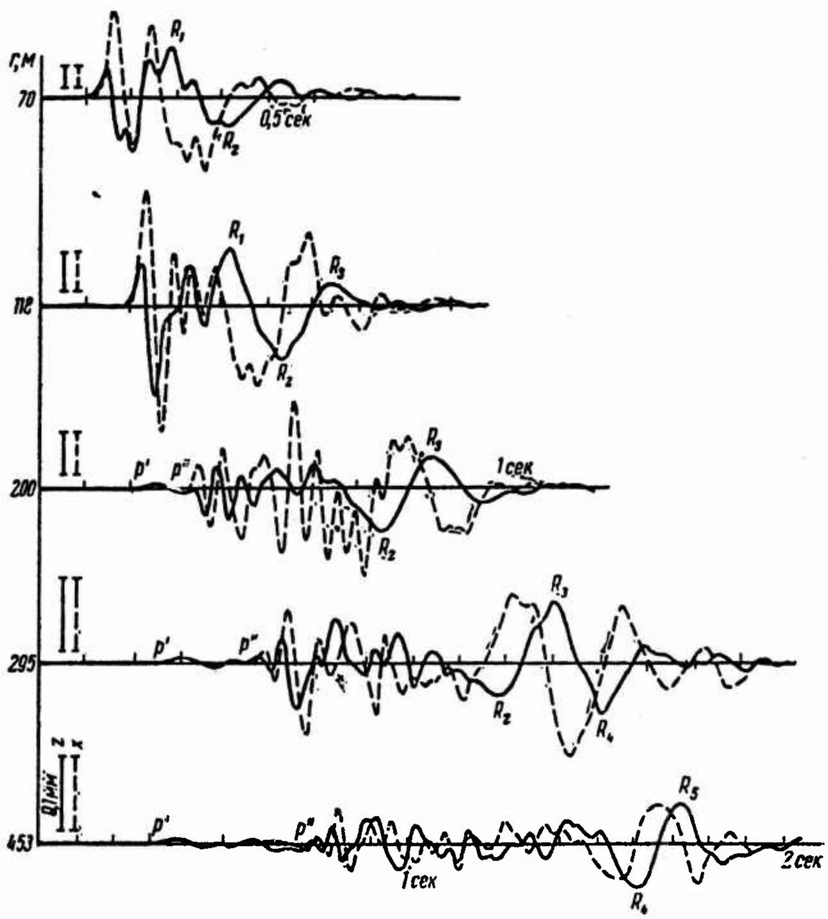

Fig. 12. Seismograms of the explosion of a 160 kg charge at a depth of 22.65 m; p, N, R - phases of the different waves.

(Fig. 14), i.e., just as in direct waves. Within the range of tracking of wave p' a long-period wave N' characterized by low intensity also is observed and as well as during explosions of charges at shallow depths (see Fig. 11). On hodograph its phases are designated by indices - N_1', N_2', etc. (see Fig. 13). The wave propagation velocity N_1 is the same as wave p'. Consequently, the long-period wave N, refracting at the boundary, produces a leading wave N'. This is the essential criterion according to which wave N can be related to a type of volumetric waves, and to velocities - related to a type of volumetric longitudinal waves.

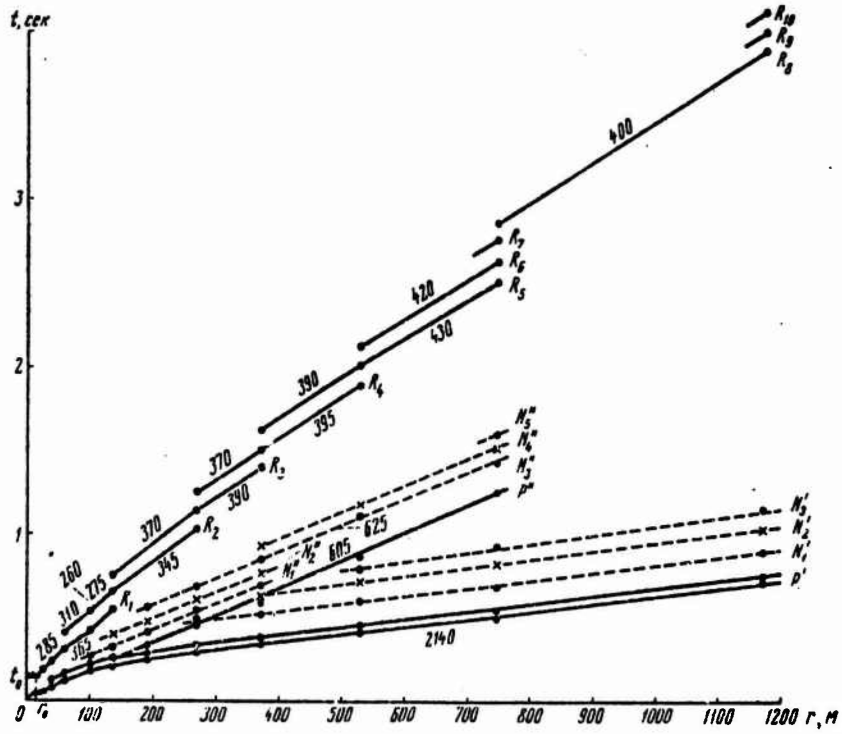

Fig. 13. Hodographs of waves during an explosion in loess-like loam.

The boundary at a depth of 50 m was the reason for the appearance of supplementary waves of considerable intensity - p" and N" (see Fig. 11 and 12). They are observed during subsequent arrivals (following waves p' and N') and have identical velocities of propagation. Wave N" predominates during explosions at a shallow depth, while wave p" predominates during explosions at a great depth. With distance both waves attenuate according to the law $a \approx r^{-1,4}$, i.e., approximately as surface waves. This one of the criteria, on which waves p" and N" can be related to longitudinal waves reflected beyond the critical angle, since the wave energy is retained in a specific layer.

Description of such waves p_g reflected from the Mokhorovichich boundary in the earth's crust, is given in [8].

Let us note that these waves have the large number of arrivals which are quite visible on the horizontal

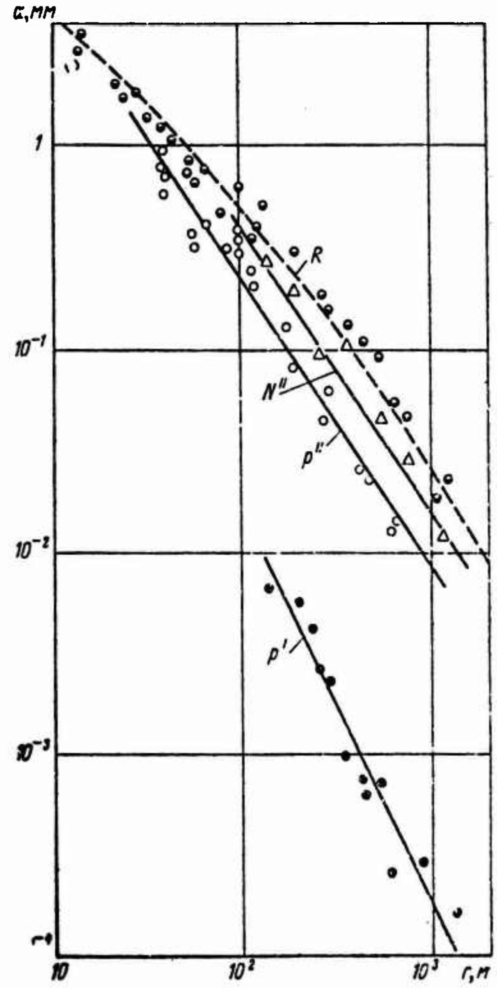

Fig. 14. Curves of the dependence of the maximum displacement of the different waves in loess-like loam.

component (see Fig. 12). The arrivals are the result of the fact that wave p" acts over a small interval of time. For wave N" which has great length, the period and duration of the action, the arrivals are not separated, but a clear dispersion as the consequence of the interference nature of this group of waves is characteristic for it. (Fig. 15).

Thus, a sharp interface can give a very intense longitudinal wave reflected beyond the critical angle. According to the velocity of the oscillations of the particles, it can considerably exceed all the waves and can become the most dangerous one for structures.

At the smallest velocities one of the most intense waves is propagated - Rayleigh's surface wave (see Fig. 15). Its maximum amplitude of displacement in loess deposits decreases with distance according to the same law, as in granites. From the parameters of the wave there is a group of velocities of interest to us. Dispersive curves of the group velocities determined by a conventional method are taken when following the moment of propagation of the elastic waves and the moment of detonation of the explosive substance: they are shown in Fig. 16a. Since the group velocity is to a

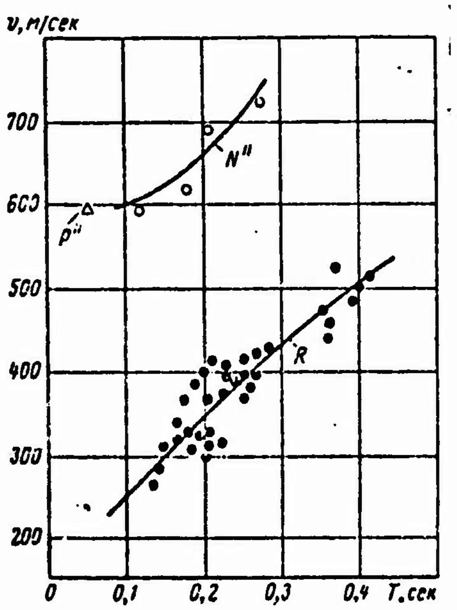

Fig. 15. Dispersive curves of the phase wave velocity R and N".

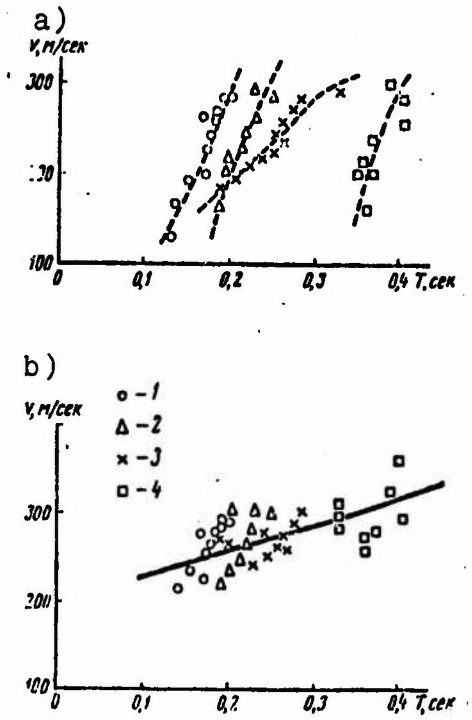

Fig. 16. Dispersive curves of the group velocities of Rayleigh's surface wave: a) not allowing for the size of the source; b) taking into account the size of the source: 1 - q = 20 kg; 2 - q = 160 kg; 3 - q = 1 t; 4 - q = 10 t.

certain degree the characteristic of the medium (if we examine one wave mode), then there should be no dependence of group velocity on the magnitude of the charge. If we turn to the hodograph of the first phase for wave R_1 (see Fig. 13), then it is easy to note that up to $r_0 = r_{\text{упр}}$ the maximum of this phase is reached at the same point in time t_0. The soil in the determined range of the epicenter (approximately radius r) heaves simultaneously, reaching its maximum at point in time t_0 and only after this, phase R_1 begins to be propagated along the surface, i.e., becomes strictly a wave. In Fig. 1, where notations of the displacement in the epicenter are represented, this - the second maximum (the first is related to wave p).

Since wave R is propagated by the second source, then apparently, r_0 is the size of this source, and t_0 by the initiation of its action. If we accept the initial parameters of Rayleigh's wave r_0 and t_0, and determine the group velocities, then we will obtain a more specific result (see Fig. 16b). It is possible that the sizes of the source are somewhat greater, but its actions will begin somewhat earlier, since, apparently, it is necessary to consider a small part of the elastic zone, but in the first approximation, the order of the obtained values, obviously, is correct. Subsequently, the size of the source will be determined by other methods. For the investigated site according to the averaged datum, obtained by all methods, it was determined that there is a dependence of the size of the source on the magnitude of the charge $r_{\text{упр}} = 2.5\ q^{1/3}$. The sizes of the source determined according to this formula and in the hodograph, agree quite well. The time of the initiation of the action of the source also depends on the magnitude of the charge, but to a lesser degree: $t_0 = 0.06\ q^{1/6}$. It is necessary to note that t_0 can depend on the depth of placement of the charge. On the hodographs it was noted that with an increase in the depth of the placement of the charge, t_0 decreases.

Parameters of Rayleigh's Surface Wave

The changes in the maximum displacement in wave R depending on the distance, are characterized by the curve given in Fig. 17. In the near zone the maximum displacements attenuate with distance according to the law $a \approx r^{-4}$. Beginning with $r = r_{\text{упр}} = 4.5 \sqrt[3]{q}$, the exponent changes with r. For all distances the dependence $a = f(r)$ is approximated by the formula

$$a = \frac{e^{-1.75\bar{r}^{0.2}}}{\bar{r}^{0.5}}, \qquad (1)$$

where

$$\bar{r} = \frac{r}{q^{1/3}}.$$

Given below are certain values of the maximum amplitudes calculated according to this formula

$\bar{r}$	1	2	5	10	20	50
a	$17{,}4\cdot10^{-2}$	$9{,}5\cdot10^{-2}$	$4\cdot10^{-2}$	$2\cdot10^{-2}$	$9{,}3\cdot10^{-3}$	$3{,}08\cdot10^{-3}$
$\bar{r}$	100	200	500	1000	2000	3000
a	$1{,}23\cdot10^{-3}$	$4{,}58\cdot10^{-4}$	$1{,}03\cdot10^{-4}$	$3\cdot10^{-5}$	$7{,}5\cdot10^{-6}$	$3{,}2\cdot10^{-6}$.

During observations at sites with different soil conditions deviations from dependence (1) were not noted (within the limits of the accuracy of the experiment). Therefore, the coefficients determined by soil conditions, by the placement depth of the charge and by the explosive force, were found on the basis of this dependence.

In [4] a formula is given for determining the maximum displacement

$$\frac{a}{q^{\eta}} = Kf(\bar{r}), \qquad (2)$$

where K and η - coefficients which depend on the properties of the rock or soil in which the explosion is set off.

The processing of all materials based on the quantitative dependences of the parameters of the waves was carried out by a graphic method since it is less laborious. In order to be convinced of the fact that the graphic method gives results with sufficient accuracy, the processing of the surface wave parameters in loess deposits was conducted by a more precise method - the least squares.

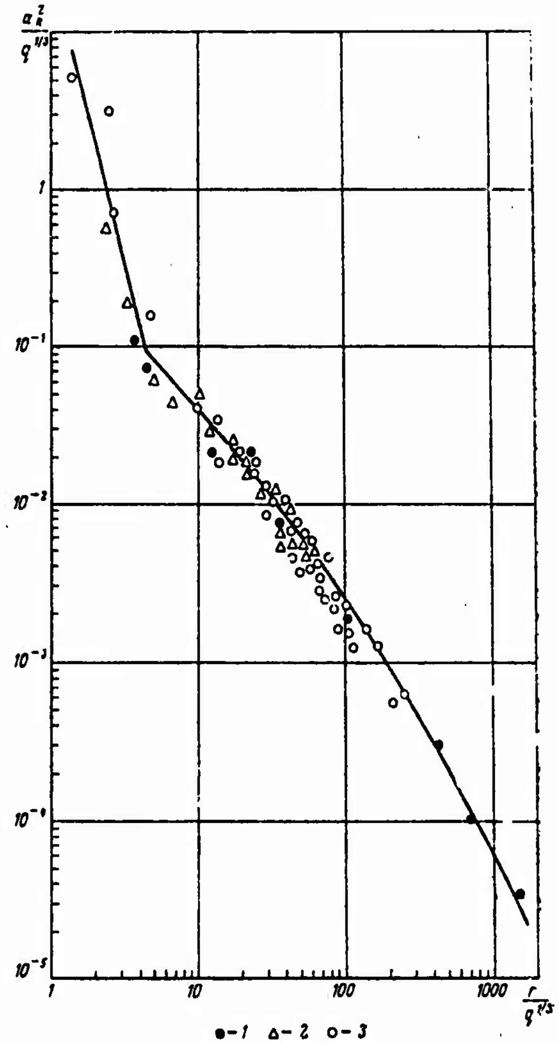

Fig. 17. Curve of the dependence of the given amplitude Rayleigh's wave on the given distance during explosions of different force in granites: 1 - q = 150 t; 2 - q = 10 t; 3 - q = 1 t.

Let us convert formula (2)

$$Kq^{\eta} = \frac{a}{f(r)} = A. \tag{3}$$

Then

$$\eta = \frac{m \Sigma \lg q_i \lg A_i - (\Sigma \lg q_i)(\Sigma \lg A_i)}{m \Sigma \lg^2 q_i - (\Sigma \lg q_i)^2}, \tag{3a}$$

where m - number of observations. The addition is made from i = 1 up to i = m.

$$\varepsilon_{\eta} = \left[\frac{\Sigma\varepsilon_i^2}{m-2}\right]^{1/2} \cdot \left[\frac{m}{m\Sigma \lg^2 q_i - (\Sigma \lg q_i)^2}\right]^{1/2}, \qquad (3b)$$

where ε_{η} - mean quadratic error η.

$$\lg K = \frac{1}{m}(\Sigma \lg A_i - \eta \Sigma \lg q_i), \qquad (3c)$$

The mean quadratic error K not allowing for error η is determined from the formula

$$\lg \varepsilon_K = \left[\frac{\Sigma\varepsilon_i^2}{m(m-1)}\right]^{1/2}. \qquad (3d)$$

where $$\varepsilon_i = \lg K + \eta \lg q_i - \lg A_i.$$

By processing, the following values are obtained for coefficients η and K: $\eta = 0.235 \pm 0.016$; $K = 15 \pm 0.52$ (with a mean value $\eta = 0.24$).

Graphically it was found that $\eta = 0.25$ and $K = 15$. By substituting the value of coefficients η and K in formula for the maximum displacement in wave R, we will obtain

$$a = 15 q^{0.24} f(\bar{r}). \qquad (4)$$

Figure 18 shows the curves of dependence a = f(r) plotted according to measurements. The curves correspond to formula (4). Curves of the dependence of the value of periods T on the distances for explosions of a scale series, are given in Fig. 19. This dependence was approximated by an exponential function. The exponent n for different explosions was determined from formulas analogous to formula (3). The following values of n were obtained.

q, кг	20	160	1000	10 000
n	0,104±0,014	0,104±0,010	0,107±0,018	0,107±0,013

For all explosions a single value n = 0.11, was taken. Then, dependence T = $\phi(r)$ can be expressed by the formula

$$\frac{T}{q^{\tau}} = K_T \bar{r}^{0.11}.$$

Using the same method for the determination of the coefficient in formula as for the displacement, we will obtain α = 0.160 ± 0.006; K = 0.060 ± 0.0006 (when α = 1/6). Finally, the formula for determining the periods will take the form

$$T = 0{,}06\, q^{1/6} \bar{r}^{0{,}11}. \quad (5)$$

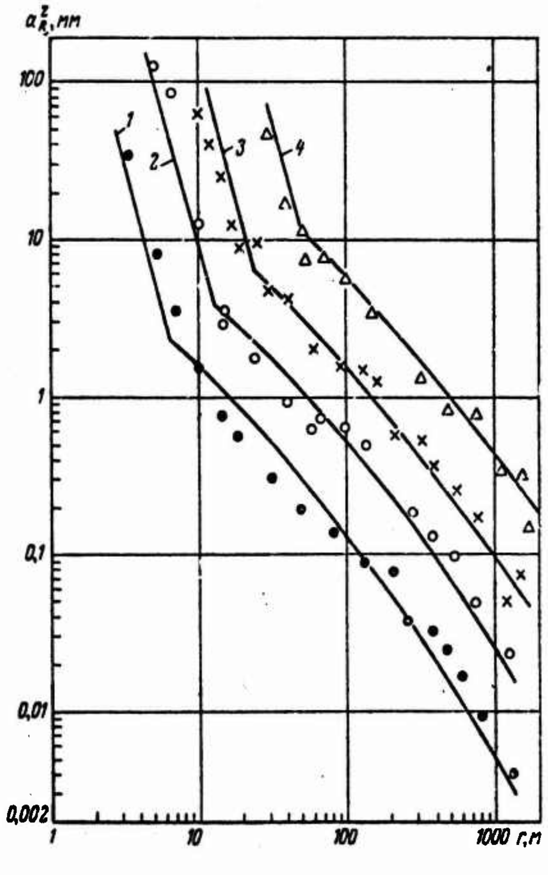

Fig. 18. Curves of dependence a = f(r) for wave R during explosions in loess deposits using charges of different force: 1 - q = 20 kg; 2 - q = 160 kg; 3 - q = 1 t; 4 - q = 10 t.

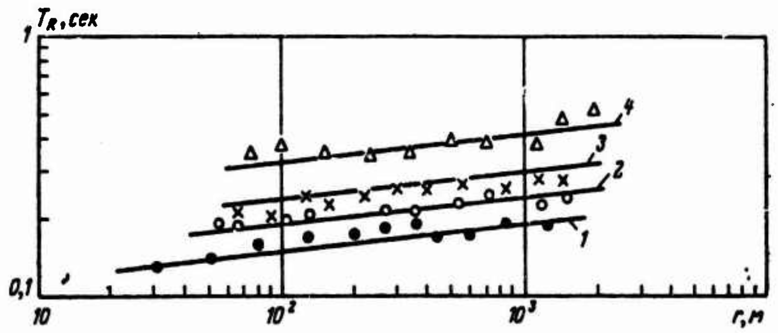

Fig. 19. Curves of dependence T = f(r) for wave R during explosions in loess deposits using charges of different force: 1 - q = = 20 kg; 2 - q = 160 kg; 3 - q = 1 t; 4 - q = 10 t.

The straight lines in Fig. 19 correspond to formula (5). The coefficients determined graphically, have the same values, as those obtained by the method of least squares.

Maximum particle speeds u_R were determined according to the slope angle of the tangent to the notation of displacement. Thus, all three basic parameters of the surfaces of the wave: displacement, particle speed and period were determined independently of each other It is not difficult to ascertain that they are connected by relationship $u_R = 2\pi(a/T)$ which corresponds to the sinusoidal law. Therefore, in the main phase waveform in the first approximation, the sinusoidal function can be approximated. On the strength of this, according to formulas (4) and (5) the dependence of particle speed on the weight of charge and the given distance is obtained:

$$u_R = K_{u_R} q^{\beta} \frac{f(\bar{r})}{\bar{r}^{\alpha}},$$

where

$$K_{u_R} = 0,2\pi \frac{K_a}{K_T};$$

$$\beta = \eta - \alpha,$$

or

$$u_R = 157\, q^{0.07} \frac{f(\bar{r})}{\bar{r}^{0.11}}. \qquad (6)$$

Figure 20 gives the curves of dependence $u_R = \psi(r)$. The data for plotting the graphs were determined according to formula (6). It is possible to determine index β and coefficient K_{u_R}, by using formulas (3). In this case depending on distance, it takes the form $f(\bar{r})/\bar{r}^{0.11}$. By calculation one found that $\beta = 0.058 \pm \pm 0.014$; $K_u = 152 \pm 4.56$ (when $\beta = 0.07$). Hence it is apparent that the determination of the particle speed on the slope angle of the notation of displacement and the recalculation based on displacement and periods, give values which are distinguished within the limits of the accuracy of observation and treatment. The processing of the observed data by the method of least squares in this stage of investigations is not necessary, since the values of the parameters determined graphically, are slightly refined.

For coefficient K there is a general law: it decreases with an increase in the strength of the rock or soil in which the explosion is set off. The stronger the rock or soil, the less the amplitude of the displacement of the main phase of the surface wave [9-10].

Earlier it was incomprehensible why a deviation in the amplitudes of displacement from the law of energy similarity takes place, and also the dependence of coefficient η on the properties of the medium were unexplained. Value η at some sites differed by 1/3. So, in granites and marbled limestone $\eta = 1/3$, in loess deposits $\eta = 0.25$, in clays $\eta = 0.22$, in water-saturated sands $\eta = 1/6$. Comparing these values with the structure of the sites, it is easy to note that in homogeneous or weakly graded media,

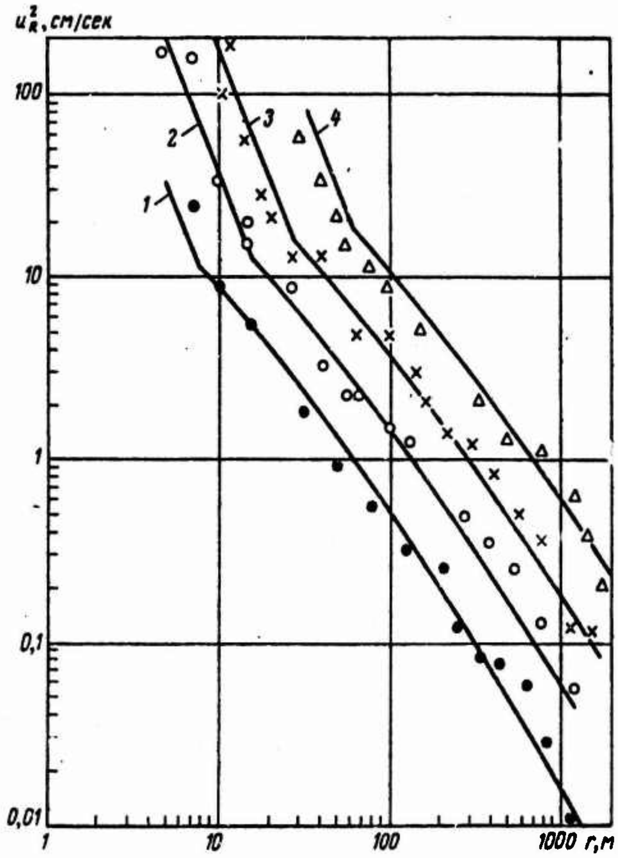

Fig. 20. Curves of dependence $u_R = \psi(r)$ during explosions in loess deposits using charges of different force: 1 - q = 20 kg; 2 - q = 160 kg; 3 - q = 1 t; 4 - q = 10 t.

where $\eta = 1/3$, the law of energy similarity obeys accurately (see Fig. 3). Where η differs from 1/3, the strong heterogeneity of the structure of the medium with depth (see Fig. 10) is observed. For sites composed of clays and water-saturated sands, high-speed profiles were not obtained, but the degree of heterogeneity of the structure of the medium with depth can be evaluated indirectly. In [4] a dependence of the phase velocities on the magnitude of the charge is given:

$$v_0 = K_0 q^{\frac{1}{3}}.$$

For loess deposits, clays and sands the exponent ξ is equal to 0.08; 0.11; 0.17, respectively.

Between v_0 and q there is this relationship. A charge with a force q excites a surface wave with a period T, which corresponds to a phase velocity v_0, which in turn, corresponds to a dispersive curve for this site. Consequently, the greater the ξ, the greater the wave dispersion and the more significant is the gradient of the properties of the medium with depth.

Formulas for displacement are obtained on the basis of these scale series of explosions which were carried out at identical given depths $\bar{h}_3 = h_3/q^{1/3}$. During such explosions the large charges based on power, are exploded at a greater depth in rock or soil of greater strength than charges of low power. Therefore, in formula (2) the value η must be considered as constant and equal to 1/3, but coefficient K as a variable even for one site, if it has a weakly graded structure. It is easy to note that after accepting $\eta = 1/3$, we will obtain a new coefficient $K_1 = K/q^{1/3-\eta}$, which agrees with the general law noted earlier.

On a site composed of loess deposits, an investigation was conducted for an estimate of the effect of the heterogeneity of the medium with depth on the parameters of the waves. Besides the scale series of the explosions using charges from 20 kg to 10 t in weight, at a given depth $h_3 = 0.7$, a deep series of 9 explosions using charges 160 kg in weight at depths from 0 to 22.6 m was conducted. The comparison of the results of both series along with the structure of the site made it possible to evaluate the effect of the heterogeneity of the medium with depth and, most importantly, the nature of the dependence of displacement on the properties of the medium, and also to confirm the adherence of the law of similarity for displacement into the surface wave. According to the data of four of them, curves given in Fig. 21

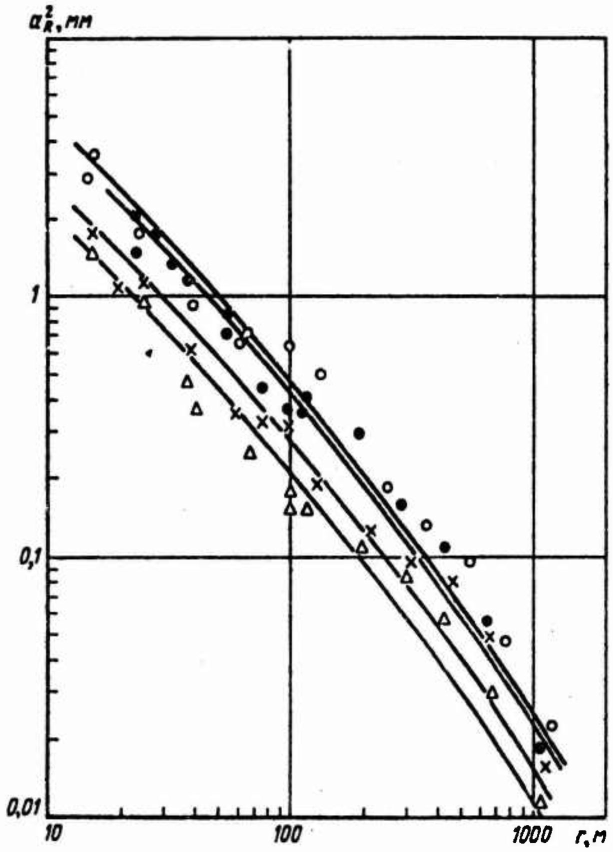

Fig. 21. Curves of the dependence of displacement into wave R, on the placement depth of the charge of 160 kg during explosions in loess deposits: 1 - h_3 = 1.25 m; 2 - h_3 = 3.75 m; 3 - h_3 = 10.4 m; 4 - h_3 = 22.5 m.

were plotted, and the total coefficient of depth α_0 (Fig. 22) was determined which depends on depth as a geometric factor, and which also depends on the properties of the medium which change with depth. Let us note that Fig. 8 gives the total coefficient of depth α_0. It is the ratio of displacement at a depth h_3 to the displacement at depth h_3 = 3.75 ($\bar{h}_3$ = 0.7), for which formula (4) is obtained. Therefore, by combining

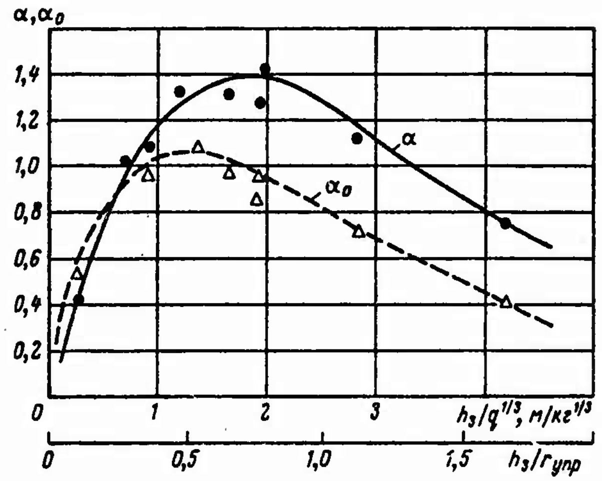

Fig. 22. Curve of the dependence of displacement into wave R, on depth.

the results of the scale and deep series of explosions, we will obtain the formula which reflects the dependence of displacement on the weight of the charges and on the depth of their placement,

$$a = 15 q^{0.24} \alpha_0 f(\bar{r}). \qquad (7)$$

However, since at this site the structure has strong heterogeneity with depth, then both the coefficient K = 15 (its numerical value corresponds to a depth h_3 = 0.7), and the coefficient of the effect of depth α_0 depend on each of the two factors: heterogeneity of the medium with depth, and the depth as a geometric value. After assuming that a geometric similarity should be observed in the formula for displacement into surface wave it is possible to convert formula (4) in the following manner:

$$\frac{a}{q^{1/3}} = \frac{15}{q^{0.08}} f(\bar{r}),$$

i.e., one can consider that the explosions of the scale series carried out at an identical given depth and at different absolute depths as a result of the heterogeneity of the medium

with depth, should have different coefficients, numerically equal to $K_1 = 15/q^{0.08}$ and depending on the properties of the media. Value K_1 in Fig. 23 is compared with the velocity of a longitudinal wave v_p, which in this case is the characteristic of the medium. From the figure one can see that K_1 is inversely proportional to v_p. On the strength of this, it is not difficult to obtain the formula for determining the displacement into surface wave during explosions in loess deposits

$$\frac{a}{q^{1/3}} = \frac{4440}{v_p} \alpha f(\bar{r}). \qquad (8)$$

Coefficient α differs from the analogous coefficient α_0. It does not take into consideration the factor of heterogeneity of the medium with depth. Coefficient α is determined from the expression

$$15 q^{0.24} \alpha_0 = \frac{4440 q^{1/3}}{v_p} \alpha.$$

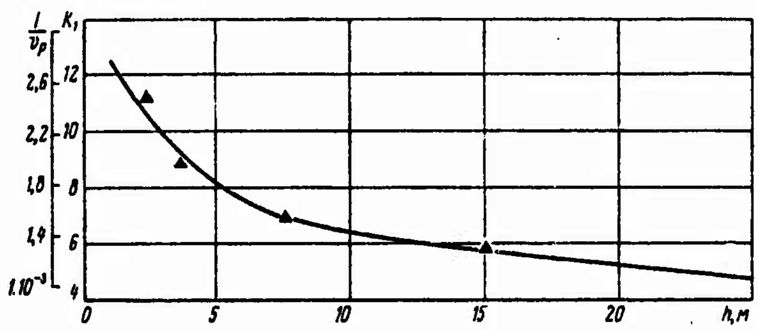

Fig. 23. Curve of the dependence of coefficient K_1 on the placement depth of the charge.

On the curve of the dependence of displacement into surface wave, on the given depth (see Fig. 22) a considerable deviation of the maximum of displacement to the side of greater depths was noted. The maximum of displacement falls at a depth

$h_3 \approx 2\sqrt[3]{q}$, which by value is close to the radius of destruction and the beginning of the elastic zone. Consequently, when the depth of the charge exceeds the dimensions of the zone of failures, the intensity of the surface wave begins to decrease. This occurs due to the fact that the elastic stresses, which are the cause for the secondary source, are not completely removed.

Let us compare these results with analogous observations in clay [5]. The maximum of displacement of the surface wave falls at the given depth $\bar{h}_3 = 3\text{-}4$. Since the structure of the site is nonhomogeneous with depth, this value corresponds to the maximum of displacement of the surface wave into loess deposits where the effect of the heterogeneity of the medium is not eliminated. The maximum of displacement during an explosion in clay should be greater. For the radius of destruction a value $r_{\text{упр}} = 6\text{-}8 \cdot \sqrt[3]{q}$ is given, i.e., the ratio of the radius of destruction to the depth which corresponds to the maximum of displacement of the surface wave, is approximately equal to two. If we introduce corrections for the heterogeneity of the medium in the curve of the dependence of displacement in clay on the depth, then latter, apparently, will be close to $r_{\text{упр}}$ in value. By comparing these data, and also taking into consideration the nature of the origin, it is possible to assume for all soils a generality of the dependence of displacement into the surface wave on the depth at coordinates $\alpha - h_3/r_{\text{упр}}$. Thus, one additional criterion is obtained to evaluate the dimensions of the origin.

It was shown that the displacements into the surface wave obey the law of geometric similarity. The observed deviation from this law during the examination of the results of explosions of scale series occurred as a result of the heterogeneous deep structure of the medium. More powerful explosions, according to the law of geometric similarity, were carried out at greater depths, where the medium is stronger and coefficient K_1 has less

value. Therefore, at the given coordinates the displacements from the different explosions according to force in the heterogeneous media are stratified and occupy a certain area (Fig. 24). During the studies of seismic waves from explosions in loess deposits it was explained that the displacement into surface wave are inversely proportional to the velocity of propagation of the longitudinal waves recorded in the vicinities of the explosion. By utilizing the speed data on longitudinal waves at different depths (see Fig. 10), formula (8) is obtained for determining the displacement of the surface wave in loess deposits. In Fig. 25, where curves are given for the dependence of the value of displacement on the distance and on the weight of the charge taking into account the correction for velocity, curve 3 corresponds to formula (8). Granites near the surface to a considerable degree are heterogeneous and fissured. Therefore, high-speed profiles cannot be used, since at shallow depths large heterogeneity of the medium on the horizontal plane is observed. To evaluate the velocity of the longitudinal waves their values obtained from the hodograph of the first displacement in the initial section were utilized. In the examined explosions they changed from 4000 to 4600 m/s; therefore, the average value of 4300 m/s is accepted (see Table 1). In marbled limestone no matter where two explosions were set off, v_p = 5200 m/s. The velocities of the longitudinal waves in clay during the explosion of a 1000 t charge were 1800-2000 m/s, and during the explosion of a 100 kg charge they were 750 m/s. In water-saturated sand v_p = 1200-1800 m/s.

It is easy to note that the curves of the displacement in different soils differ by value according to level, directly proportional to $r_{упр}$. It was possible even earlier to assume that the size of the origin should somehow be considered during the calculation of the displacement. Taking into account this factor, the formula for determining the displacement into the surface wave P can be presented in the following form:

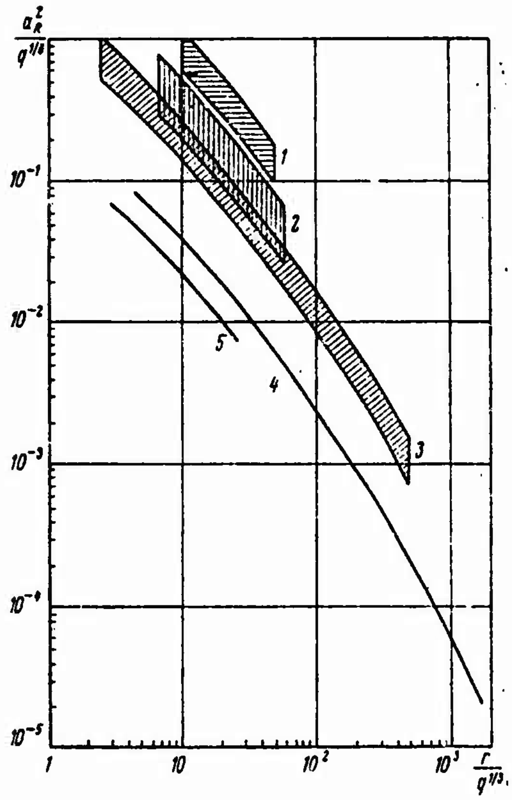

Fig. 24. Curves of dependence $a^2R/q^{1/3} = f(r/q^{1/3})$ during explosions in water-saturated sand 1, clay 2, loess deposits 3, granite 4, marbled limestone 5.

$$a_R^2 = 1900 \frac{r_{\text{упр}}}{v_p} f(\bar{r}).$$

On the basis of the data obtained by the calculation according to this formula, and according to observations during explosions in different soils, the curve, given in Fig. 26, is plotted. Taking into account the effect of the placement depth of the charge, the final formula will take the form

$$a_R^2 = 1900 \frac{r_{\text{упр}}}{v_p} \alpha\left(\frac{h_3}{r_{\text{упр}}}\right) f(\bar{r}), \qquad (9)$$

where $\alpha(h_3/r_{\text{упр}})$ - function of the effect of the placement depth of the charge (see Fig. 22).

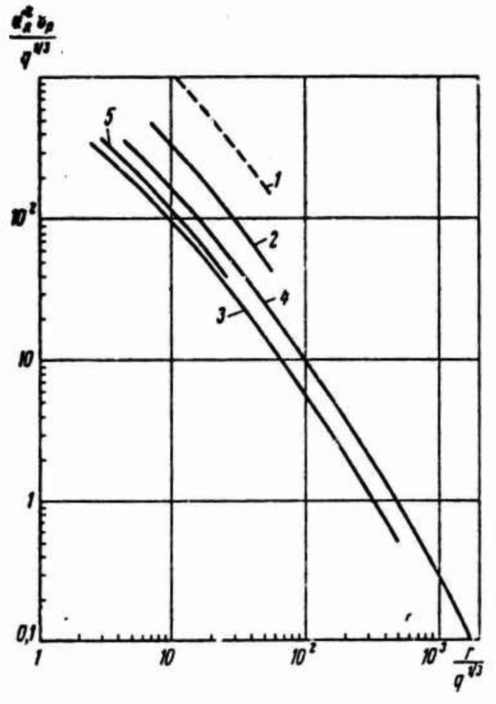

Fig. 25. Curves of the dependence of the given displacement of soil into the surface wave on given distances during explosions in different soils taking into account the velocity of propagation of the longitudinal waves: 1 - water-saturated sand; 2 - clay; 3 - loess deposits; 4 - granite; 5 - marbled limestone.

The horizontal component is shifted in phase relative to the vertical in the fourth period; therefore, during the passage of wave R the trajectory of the particle motion is elliptical. The ratio of the maximum amplitudes according to z and x - component which depends on the properties of the medium: in granite it is 0.86, in clay, 1, and in loess deposits, 1.6. In a uniform half-space, the ratio a_R^x/a_R^z on the surface should depend only on the Poisson ratio. One can assume that for laminar and gradient media the Poisson ratio will also be one of the main factors which affect the value of the ratio a_R^x/a_R^z. From Table 2, where data are given which show the effect of the Poisson ratio R on the parameters of wave R, it is evident that there is a relationship in the first approximation. With an increase in ν the ratio a_R^x/a_R^z increases.

At sites with gradient or laminar structure the Poisson ratio was estimated according to the ratio of the minimum of maximum from the recorded velocities of the surface (phase) and

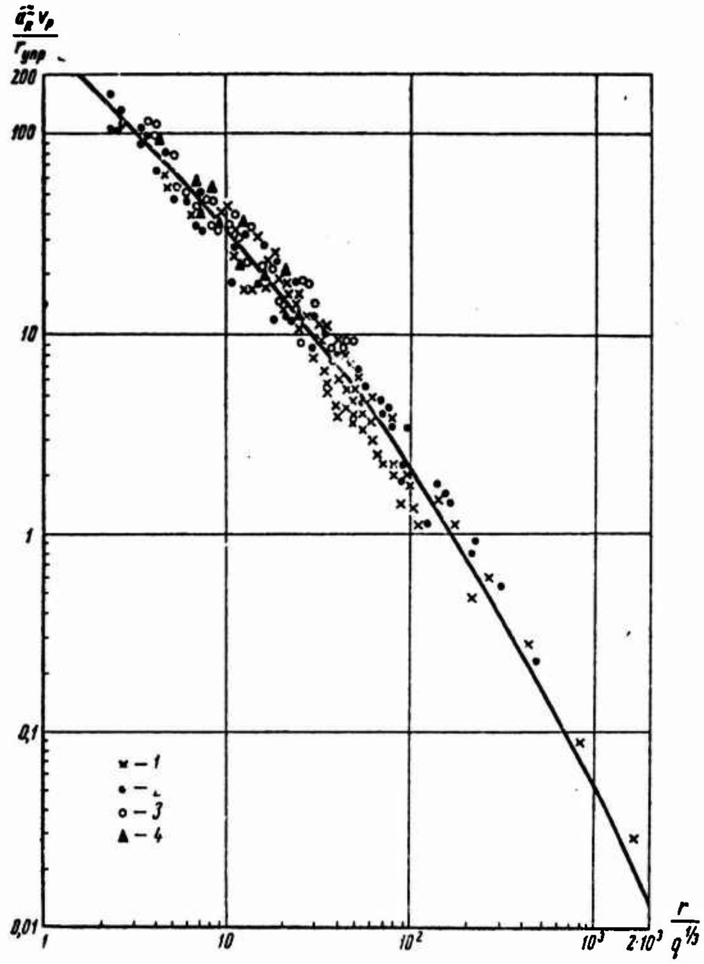

Fig. 26. Curve of the dependence of displacement into surface wave, on given distances during explosions in different rocks or soils: 1 - granite; 2 - loess deposits; 3 - clay; 4 - marbled limestone.

longitudinal waves, since in this case it is possible for one to use formulas for Rayleigh's wave in a uniform half-space.

In Rayleigh's surface wave the period was defined as the doubled time between two adjacent phases with the maximum amplitudes of displacement. Nature of a change in the periods with distance during explosions in sands and in granite is shown by curves given in Figs. 27, 28. In water-saturated sands with an

Table 2.

Rocks or soil	v_p, m/s	v_0, m/s	ν	$\frac{a_R^x}{a_R^z}$
Water-saturated sand..........	1200-1800	140-400	0.48-0.50	-
Loess deposits	400-2150	170-550	0.40-0.46	1.4-1.8
Clay..........	750-1800	330-800	0.36-0.39	1.2
Granite.......	4000-5800	2100-2500	0.26-0.36	0.6-1.1
Marbled limestone.....	5200	1850	0.41	-

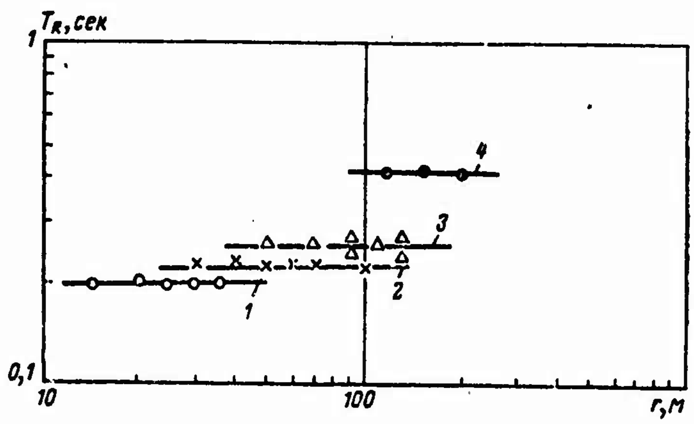

Fig. 27. Curves of dependence T = f(r) in wave R during explosions in water-saturated sands using charges of different weight: 1 - q = 5 kg; 2 - q = 10 kg; 3 - q = 40 kg; 4 - q = 320 kg.

increase in the distance, the period does not change, but increases with an increase in the weight of the charge according to the law $T \approx q^{1/6}$.

In granite a considerable increase is observed in the period with an increase in distance ($T \approx r^{0.44}$) and a very insignificant

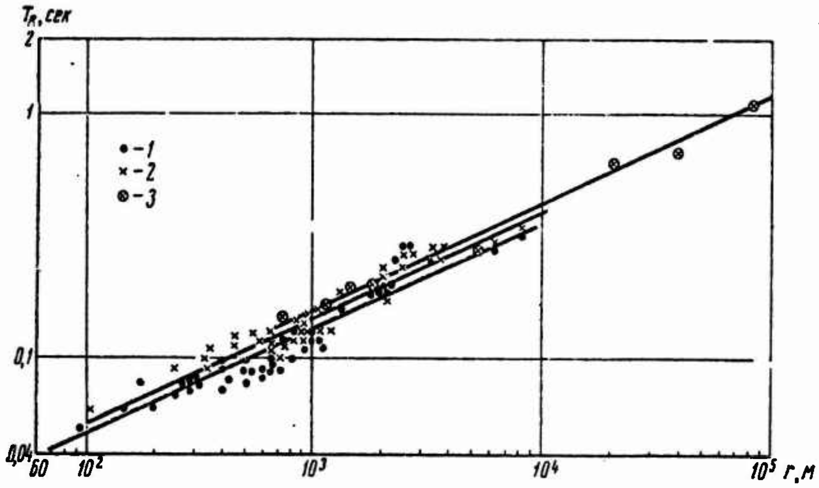

Fig. 28. Curves of dependence T = f(r) in wave R during explosions in granite using charges of different weight: 1 - q = 1 t; 2 - q = 10 t; 3 - q = 150 t.

increase in the period at a fixed distance with an increase in the weight of the charge ($T \approx q^{0.02}$). The latter dependence can hardly be noted, especially during a small change in the range of the weight of the charges. However, if we compare the periods which are observed during the explosion of charges of different weight at identical given distances $\bar{r} = rq^{-1/3}$, then they will be distinguished proportionally to value $q^{1/6}$. The corresponding curve is shown in Fig. 29. Water-saturated sands and granites are two opposite types of earth materials. In water-saturated sands the period depends only on the weight of the charge, whereas in granite - it depends only on distance. All other rock and soil materials occupy an intermediate position and they depend both on the weight of the charge and on the distance. But at identical given distances the periods for all rock and soil materials, just as for granite, are proportional to the value $q^{1/6}$. The values of the periods measured in the surface wave during explosions in different rock and soil materials,

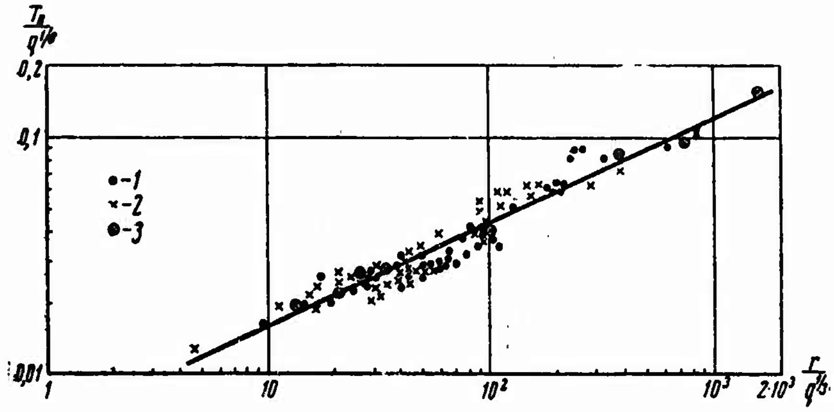

Fig. 29. Curve of the dependence of periods in the surface wave at given distances during explosions in granite: 1 - q = 1 t; 2 - q = 10 t; 3 - q = 150 t.

are shown on the curves at coordinates $T/q^{1/6}$-$r/q^{1/3}$ (Fig. 30). The nature of curves correspond to the expression

$$T_R = K_T q^{1/6} \bar{r}^n. \qquad (10)$$

Parameters of a Longitudinal Wave

At all sites for a vertical component on the surface in longitudinal wave p, the same law holds for amplitude change with distance. It usually is approximated by the exponential function in the form $a \approx r^{-n}$ ($n = 2 \pm 0.2$). By wave p are implied the waves in the first arrivals. Since the medium at the investigated sites is almost always heterogeneous in depth, this wave, as a rule, is a refracted one, and sometimes a leading wave.

The dependence $a_z \approx r^{-2}$ with a source located near the floating surface, corresponds to the solution for the displacement of the longitudinal wave which is propagated into uniform, ideally elastic medium (the wave slips along the surface) and for the leading waves in laminar medium. This same dependence is valid

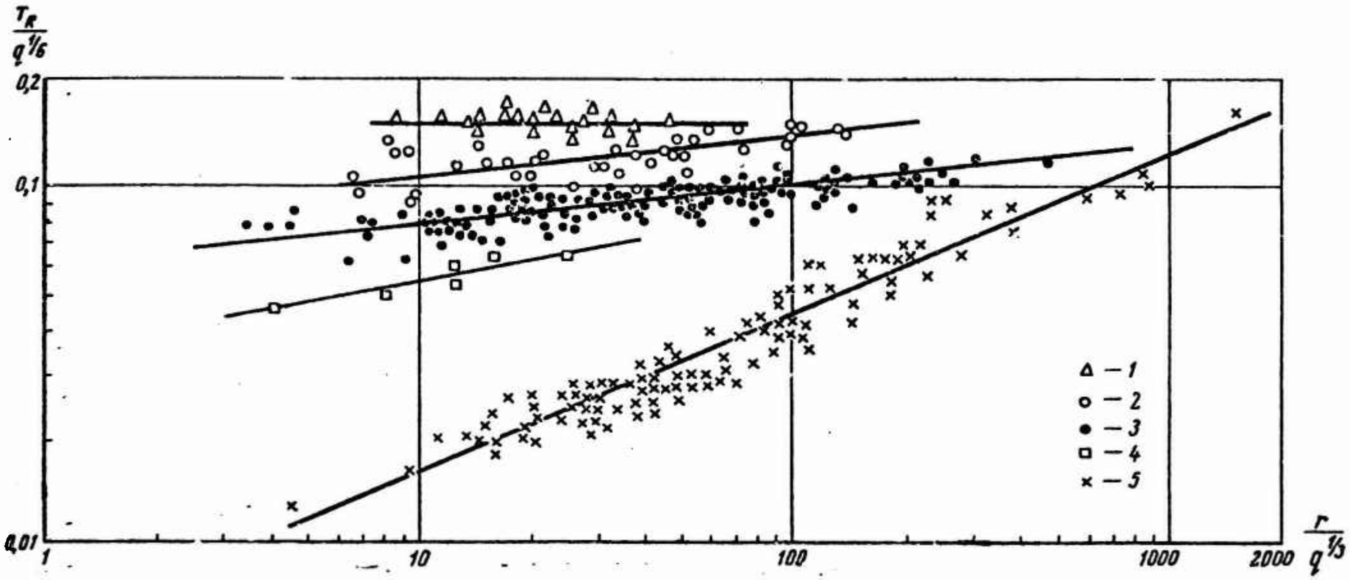

Fig. 30. Curves of the dependence of the given periods in wave R on given distances during explosions in water-saturated sand 1, clay 2, loess deposits 3, marbled limestone 4, granite 5.

also for refracted waves at large distances, i.e., where the wave in essence becomes a leading one. This case occurs at a site consisting of granites (see Fig. 3). At this site one ought to expect a conformity of the dependence $a \approx r^{-2}$ at distances of 200-300 m. At a site consisting of loess deposits, the displacements are measured in the leading wave emerging in the first arrivals at a distance of approximately 100 m from the epicenter; therefore, dependence $a_z \approx r^{-2}$ can be traced beginning at this distance.

Thus, the observations show that a decrease in the displacement with distance into the longitudinal wave, occurs only as a result of the geometric disagreement of the wave front. This is due to the fact that the observations covered a small range of distances (beginning from the epicenter), i.e., where the wave has considerable intensity in this range. The profiles were not more than several wavelengths λ. At such distances the absorption can be an insignificant factor. In connection with this, it is interesting to evaluate the possibility of the effect of absorption on the wave amplitudes. The results of this estimate are given in Table 3.

Table 3 gives data on three experiments in granite and in loess deposits using charges of different weight. Estimates of the effect of absorption are made for points at the end of the profile at a distance r_{max}. Given for a comparison are the values of the maximum vibration velocities of particles u, recorded at these distances. Table 3 shows that the dangerous velocities can be observed at closer distances. The decrement of absorption Δ_p for a granite is cited from [11], and for a loess-like loam - from [12]. The calculations show that even at those distances where the intensity of wave p becomes small, the factor which takes into consideration the effect of absorption, plays an insignificant role. Consequently, for seismic waves over short distances where they carry energy which can be hazardous for structures, absorption can not be considered.

Table 3.

(1) Порода	q, кг	T_p, сек	v_p, м/сек	λ, м	$\frac{r_{max}}{\lambda}$	Δ_p	$e^{-\Delta_p \frac{r}{\lambda}}$	u, см/сек
(2) Гранит	10^3 $1{,}5 \cdot 10^5$	0,04 0,09	5300 5300	210 480	10 15	0,03 0,03	0,75 0,64	0,02 0,05
(3) Лёсс	40	0,11	2100	230	5	0,15	0,47	0,001

KEY: (1) Rock or soil; (2) Granite; (3) Loess deposits.

The vibration velocities of particles in longitudinal wave p are measured according the slope of the tangent to the notation of displacement over a segment from the first arrival to the first maximum. The comparison of velocities at identical given distances (Fig. 31) showed that this parameter follows the law of energy similarity. During explosions in the majority of hard rocks the values of velocity are virtually identical (within the limits of the presented observation data) and do not depend on their properties. In such earthen materials as loess deposits, the value of the velocity almost an order less than in the remaining rock and soil materials. For explosions in loess deposits two curves are obtained which correspond to observations from the years 1963 and 1965. After the period between observations the moisture content humidity of loess deposits changed from 2 to 5%. Observations in 1965 showed tha large intensity of the waves. If we compare the level of the curves, it is possible to arrive at the conclusion that the vibration velocity of the particles in the wave to a great degree depend on the presence and the quantity of pores with trapped air in the rock or soil material. So, for all rock and soil which correspond to the upper curve, in spite of a strong contrast between the properties, the values of the velocity obtained are the same. All these rock and soil materials have

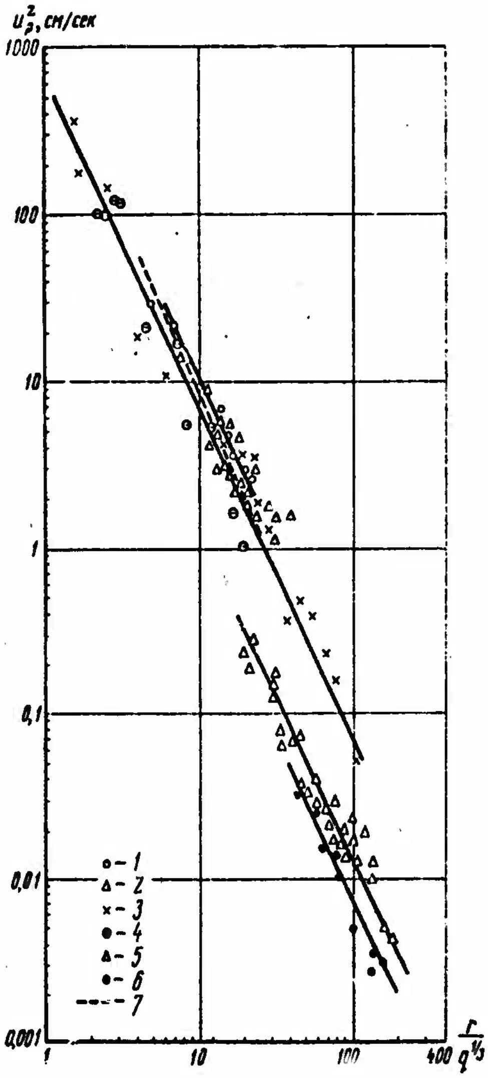

Fig. 31. Curves of the dependence of the vibration velocities of particles in wave p on a given distance.

Points	1	2	3	4	5	6	7
Rock or soil material	Clay	Water-saturated sand	Granite	Marbled limestone	Loess deposits, 5% moisture content	Loess deposits, 2% moisture content	Clay (according to [5])
Weight of the charge, kg	10^2-10^3	5-320	10^3-$15\cdot10^4$	$15\cdot10^4$ $66\cdot10^4$	10^2-$5\cdot10^3$	40	-

insignificant porosity or have pores filled with water (water-saturated sand). The effect of porosity on the compression wave (and, consequently, the elastic waves) was investigated in [13]. In all rock and soil materials the same nature of a change in the maximum vibrational velocity of particles with distance is noted, therefore, the formula for the calculation of the velocities will take the form

$$u_p^2 = K_u \left(\frac{q^{1/3}}{r} \right)^2. \quad (11)$$

The values of coefficient K_u which depends on the type of rock or soil, are given in Table 4.

The periods in the longitudinal wave estimated according to the rise time of the displacement to a maximum τ_+. This time corresponds to a quarter of the period of the longitudinal wave. Although this method gives the smallest probability of errors during processing, the spread in the determinations of the visible period is sufficiently significant. It is possible that this is connected with the heterogeneities of soil conditions at instrument installation sites. So, the most extensive spread is observed during the explosions of 1 and 10 t charges in granites (Fig. 32). And, actually, in these experiments the instruments at some points were installed not in rock outcrops, but in their thin mantle consisting of gravel, several dozen of centimeters thick. During the explosion of a 150 t charge, when all instruments were installed in the rock outcrop, and also during explosions in loess deposits (Fig. 33) the scatter of the periodic values was considerably less.

The large scatter of the periodic values during the determination of their dependence on the magnitude of the charge and

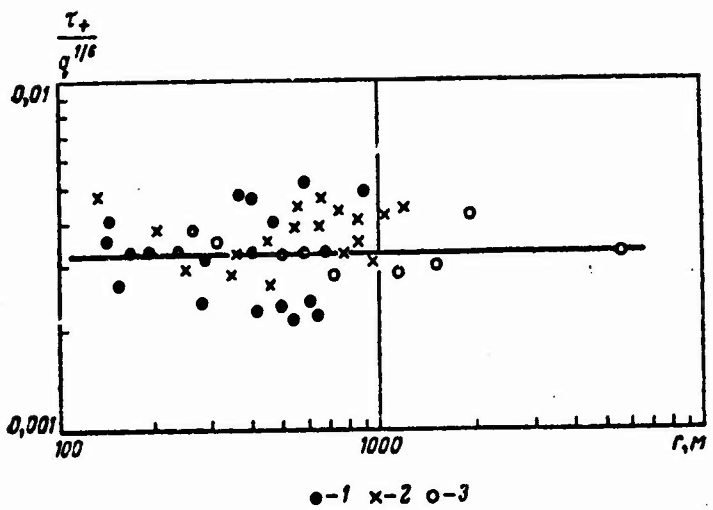

Fig. 32. Cu:.:e of the dependence of the given periods in the longitudinal wave p, on the distances during explosions in granite: 1 - q = 1 t; 2 - q = 10 t; 3 - q = 150 t.

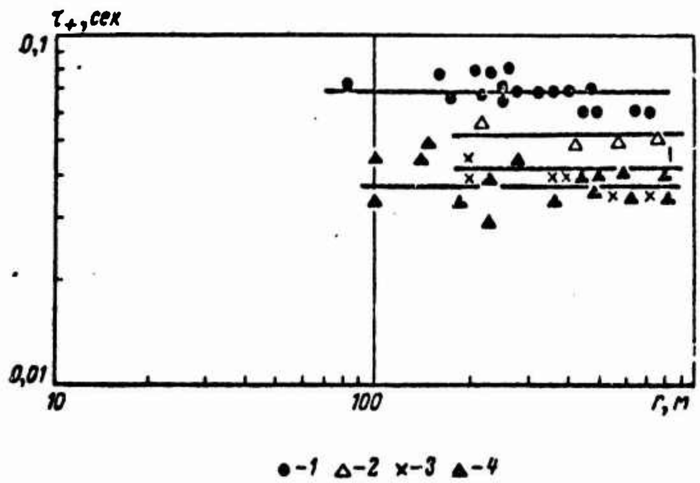

Fig. 33. Curve of the dependence of the rise time τ_+ in wave p, on the distance during explosions in loess deposits: 1 - q = 5000 kg; 2 - q = 1000 kg; 3 - q = 200 kg; 4 - q = 100 kg.

the distance in the case of a small change in the range of the latter, can lead to a great diversity of regularities. The curves in Figs. 32 and 33 show that within the limits of the scatter of the observed points, it is possible to judge the independence of the period of direct longitudinal waves on the distance. The period depends on the weight of charge proportional to value $q^{1/6}$. This dependence was also noted in [2, 5, 14]. Figure 34 shows the curves of the dependence of the given rise time in wave p on the distances plotted on the basis of observation data at all sites. According to these data the formula for the calculation of the periods or rise time τ_+, can be represented in the following form:

$$\tau_+ = K_\tau q^{1/6}, \qquad (12)$$

where K_τ - coefficient which depends on the type of rock or soil.

Values of coefficient K_τ are given in Table 4.

Table 4.

(2) Порода	(1) Волна p			Волна R	
	K_u	K_τ	K_-	K_T	n
Глина (3)	1100	75	0,01	0,08	0,11
Водонасыщенный песок (4) . .	700	60	0,015	0,15	—
Гранит (5)	700	15	0,0032	0,0058	0,44
Мраморизованный известняк (6)	700	15	0,0032	0,035	0,20
Лесс влажностью 5% (7) . . .	130	14	0,017	0,06	0,11
Лесс влажностью 2% (8) . . .	70	7,5	0,017	0,06	0,11

KEY: (1) Wave; (2) Rock or soil; (3) Clay; (4) Water-saturated sand; (5) Granite; (6) Marbled limestone; (7) Loess deposits with 5% moisture content; (8) Loess deposits with 2% moisture content.

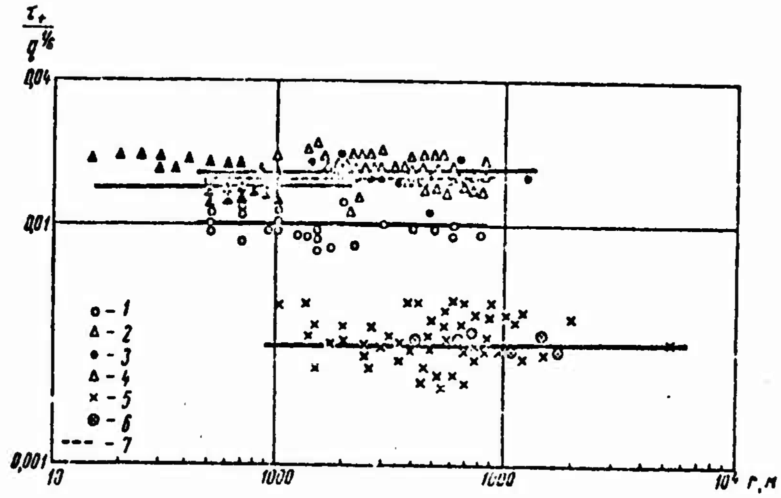

Fig. 34. Curve of the dependence of the given rise time in wave p, on the distance during explosions in different rocks and soils.

Points	1	2	3	4	5	6	7
Rock or soil	Clay	Water-saturated sand	Loess deposits, 2% moisture content	Loess deposits 5% moisture content	Granite	Marbled limestone	Clay (according to [5])
Weight of the charge, kg	10^2–10^3	5-320	40	10^2–$5\cdot10^3$	10^3–$15\cdot10^4$	$15\cdot10^4$–$66\cdot10^4$	-

Curves of the dependence of the given maximum displacement in wave p from given distances, are shown in Fig. 35. The straight lines plotted according to observations correspond to the formula

$$\frac{a_p^2}{q^{1/6}} = K_n\left(\frac{q^{1/3}}{r}\right)^s \tag{13}$$

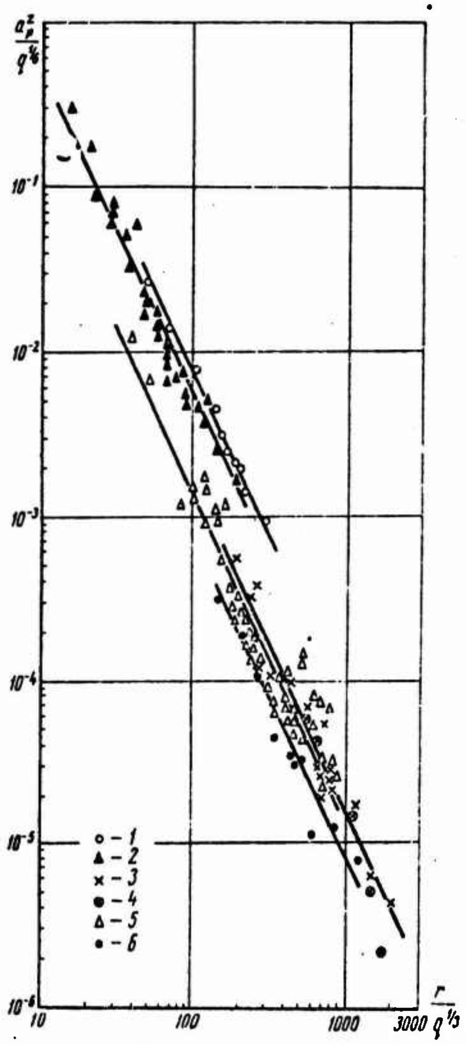

Fig. 35. Curves of the dependence of the maximum displacements into wave p on a given distance during explosions: 1 - in clay; 2 - in water-saturated sand; 3 - in granite; 4 - in marbled limestone; 5 - in loess deposits with 5% moisture content; 6 - in loess deposits with 2% moisture content.

A certain deviation from the energy law of similarity is due to the fact that a similarity for the periods is not observed. The displacements in wave p are connected with the particle speed and rise time τ_+ by a ratio $a_p = 2u_p\tau_+/\pi$, which corresponds to harmonic oscillations.

During the measurements on the surface mainly the vertical component is recorded, since at the majority of sites, the medium is heterogeneous with depth, and the longitudinal wave emerges approximately normal to the surface. The horizontal component in

wave p is insignificant on the surface and usually during the first arrivals, the displacements which relate to wave N are recorded on the horizontal. However, at points lying lower than the floating surface, wave p provides a horizontal component, whereupon the full displacement vector or velocity is approximately equal to the amplitude on the surface.

On the site composed of granites, with an increase in the weight of the charge an increase is noted in the horizontal component in the longitudinal wave on the surface. This is connected with the fact that with a gain in the weight of the charge the periods and, consequently, also the wavelength increase in the longitudinal wave. Relative to the long-period waves the site can be considered uniform (the longitudinal wave slips along the surface). For the wave which slides along the surface of a uniform half-space, in [15] the ratios between the vertical and horizontal components are given. They depend only on the properties of the medium (from Poisson ratio). So, for granite $\nu \approx 0.3$, the ratio $\frac{a_p^x}{a_p^z} = 2$. Such ratios are observed in longitudinal waves N whose length is from 500 to 2000 m, and which arbitrarily are sliding values for the examined site. The contraction in the length of the wave reduces the ratio a_p^x/a_p^z as a result of a decrease in the angle of incidence in the wave. With short-range waves a_p^x will be considerably greater than a_p^z, which most frequently is observed in wave p.

* *

*

During underground explosions along with an ordinary longitudinal wave a second, longer period wave is observed which according to its criteria (velocity of propagation, degree of

damping with distance, the ability to be reflected and to be refracted) is also related to volumetric longitudinal waves. The second wave appears as a result of the complex nature of the origin of the seismic waves during explosions near the floating surface.

The long-period longitudinal wave and Rayleigh's surface wave have the general criteria: identical values of periods and a nature of a dependence of the amplitudes of oscillations on the placement depth of the source - properties which are not connected with the passage of wave propagation, but with the parameters of the origin. Because of this the second source emits a Rayleigh's wave.

In the analysis of the results of processing seismic waves using a number of parameters, a certain distance from the burst center was found, which is related to the boundary between the inelastic and elastic zones for deformations in the soil. The zone, adjacent to this boundary (it is estimated at radius $r_{упр}$), is identified with the dimensions of the origin. Therefore, the establishment of the beginning of the elastic zone in different soils is extremely important.

Let us compare all criteria for determining this boundary during explosions in loess deposits.

1. *Based on the hodograph of the first phase* - R_1 Rayleigh's wave. The time of the maximum of the first phase (see Fig. 13) at closest distances to the epicenter has a constant value. This means that all the soil in this zone heaves simultaneously. At distance $r = r_{упр}$ the time of the maximum of phase R_1 begins to increase with velocity v_0, i.e., the motion becomes a wave. The boundary of elastic zone is estimated at a value of $r_{упр} \approx$ $\approx 2.5 \sqrt[3]{q}$.

2. *Based on a change in the degree of damping of the amplitudes and periods with distance, both in the surface and in*

longitudinal waves, in loess deposits the estimates of $r_{упр}$ are obtained according to observations of the amplitudes of the displacement of the surface wave. The average value is $r_{упр} = 2.5\sqrt[3]{q}$. It should be noted that during small explosions at shallow depths $r_{упр}$ has a greater value than during large deep explosions. This corresponds to a change in the strength of rock or soil with depth. Extreme values $r_{упр} = 2.0\text{-}2.8\sqrt[3]{q}$.

3. *Based on the maximum of the dependence of the intensity of the displacement of wave R on depth* $r_{упр} = 2\sqrt[3]{q}$.

4. *Based on observations of the deformations of the soil on the surface (at the epicenter).* This method gives a direct result, although somewhat overstated, since near the surface the zone of failures is transformed from spherical to elliptical. In conducting the explosions of a deep series in loess deposits, sketchings were made of the soil disturbances at the epicenter (Fig. 36). The latter given the depth of the charge, at which fissures are noted on the surface, was $h_3 = 2.82$. Apparently, even the boundary of the elastic zone is close to the value $r_{упр} = 3\sqrt[3]{q}$.

5. *Based on the interaction of linear-distributed charges.* The observations of seismic waves during the explosions of distributed charges[1] showed that the resulting displacement is a superposition of waves from separate explosions in the group. Since at considerable distances between the separate charges, the displacements from each charge correspond to the displacement from one isolated concentrated charge of the same weight. With the distances between the charges in a group, less than $l_{пред} = 6\sqrt[3]{q}$, the intensity of the surface waves radiated from each single charge, becomes less. This means that the origins of waves

[1]See article by B. G. Rulev and D. A. Kharin in the present collection.

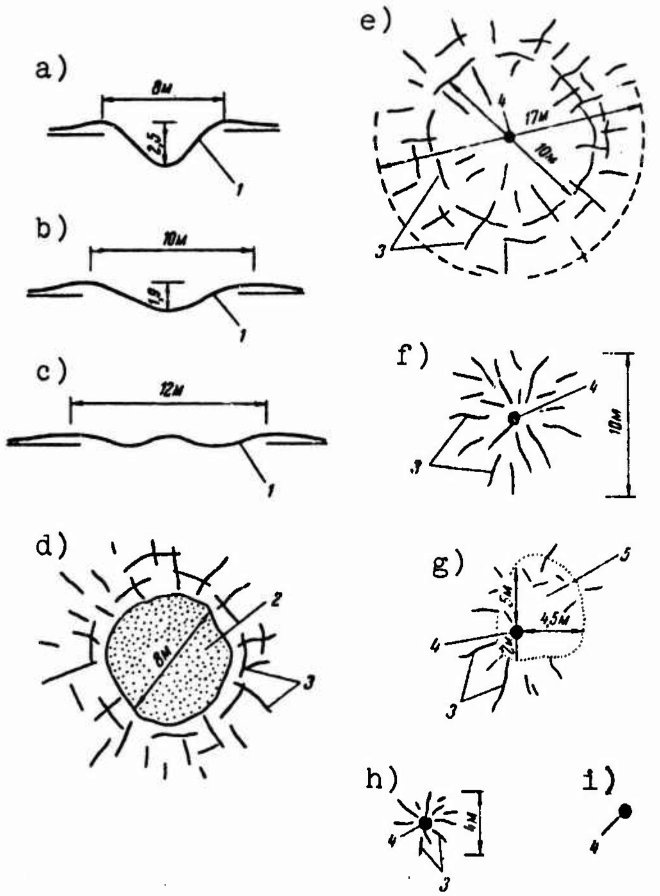

Fig. 36. Nature of soil disturbances on the surface during the explosion of 160 kg charges at different depths: a) 1.2 m; b) 3.7 m; c) 4.9 m; d) 6.4 m; e) 8.0 m; f) 10.4 m; g) 10.7 m; h) 15.3 m; i) 20.5 m; 1 - shape of the crater; 2 - loosened soil; 3 - circular and radial fissures; 4 - mouth of the bore holes; 5 - distended range.

are contiguous and begin to interact. Hence, $r_{упр} = 1/2\ l_{пред} = 3 \sqrt[3]{q}$.

In the first approximation, it is possible to consider that in loess deposits $r_{упр} \approx 2.5 \sqrt[3]{q}$ is the average for determinations by all methods. For the remaining rocks and soils, due to the limitedness of observations, the estimates of $r_{упр}$ are made according to one-two of these methods. So, for a granite - with respect to a change in the degree of damping of the amplitude of the surfaces wave - $r_{упр} = 4.5 \sqrt[3]{q}$ (Fig. 17); for a clay - according to the graphic representation of the dependence of the amplitudes of displacement on the distance, and indirectly from the maximum of the dependence of the displacement of wave R on depth [5] - $r_{упр} = 6\text{-}8 \sqrt[3]{q}$; for marbled limestone - according to the hodograph of the first phase of wave R - $r_{упр} = 3 \sqrt[3]{q}$.

Up to now the radius of the elastic zone has been considered as the strength characteristic of the medium. This is valid with insignificant variations in the initial energy concentration or loading density (0.8-1.5 t/m^3). In [16], it was shown that the volume of soil ejected by the explosion serves as a measure of both the effectiveness of the explosion and the strength of rock or soil. The volume of the forming cavity also depends on the loading density or initial value of the energy of the explosives with an identical initial volume of the explosive chamber and in one type of soil. But since the volume of the disturbed soil and the volume of the cavity, which is formed after explosion, are found to be in a direct dependence for one type of soil, $r_{упр}$ also depends on the loading density. Thus, the initial energy concentration is included in formulas of the parameters of seismic waves through $r_{упр}$.

By comparing the observed data of the parameters of seismic waves during explosions, it is possible to present the nature of the origin and, as a result, to present some quantitative relationships for the parameters of waves radiated from this origin.

First of all, this relates to the dependence of the parameters of the waves on the weight of the charge.

As a result of observations on the periods in surface and longitudinal waves an important property of these waves was revealed: at identical given distances their periods are proportional to the weight of the charge to one-sixth power. Hence, it follows that a determined similarity is observed, but it differs from the energy similarity of the particle motion of the soil. This means that the initial conditions are not simulated during the formation of elastic waves according to the law of energy similarity. Apparently, the value of the period is assigned at the very beginning of the elastic zone, on the boundary of the origin. The latter is proportional to the value $rq^{-1/3}$, and consequently, the period on the boundary of the origin is proportional to $q^{1/6}$.

The initial oscillations (wave p) are excited by the shock wave (compression wave) whose action in time relative to the oscillatory period of the elastic longitudinal wave, is equivalent to the assignment of the initial velocity. Therefore the vibration velocity of the particles in the longitudinal wave p, just as in the compression wave, obeys the law of energy similarity and is an independent parameter. The displacement into the longitudinal wave p is proportional to the product uT, and is a dependent parameter which does not retain geometric similarity.

Secondary oscillations appear as a result of the release of the elastic stresses σ_{CT} which contain the residual pressure in the cavity. In the investigated case the cause for the excitation of oscillations are the initial displacements caused by the action of stresses σ_{CT}. Both those and others retain a geometric similarity and are independent parameters for waves N and R. The particle speed in waves N and R are proportional to the value $q^{1/6}$ at similar distances $rq^{-1/3}$ according to the ratio $u \approx a/T$.

Curves of the dependence of stresses, particle speed and displacement into the zone of the formation of elastic waves on time, are shown in Fig. 37. The initial disturbances (up to the dotted line) appear during the action of the first source. The second, longer period oscillations are excited only during explosions near the floating surface. Based on time these oscillations, apparently, are contiguous and coincide with each other. For parameters σ, u, a, T and others, the degree of their proportionality by magnitude of the charge at identical given distances $\bar{r}$ is different, namely: parameters $\tau_{п}$, σ_1, u_p, $\sigma_{cб}$ and a_2 are proportional to $q^{1/3}$, but parameters τ_+, $t_{cб}$, u_2, a_p and T are proportional to $q^{1/6}$. For both groups of waves these relationships are different even for the same parameters. Therefore, at a specified given distance, but different in explosive force, those or other waves can predominate.

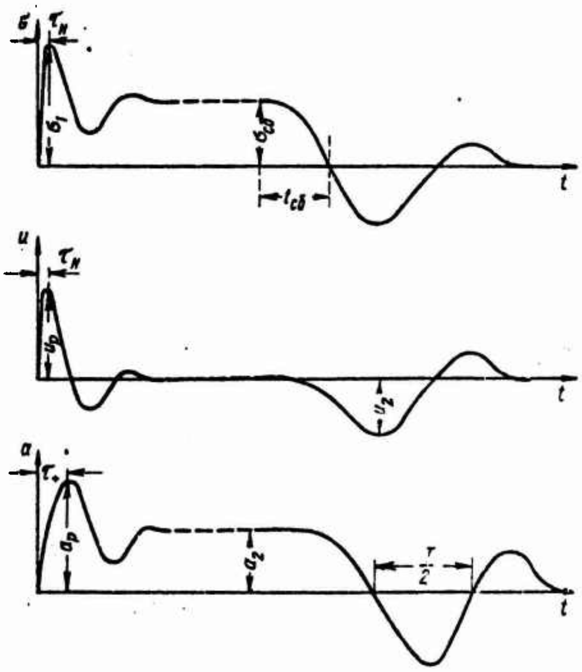

Fig. 37. Schematic graphic representations of the dependence of stresses, displacements and particle speeds into the zone of the formation of the elastic waves, on time.

In conclusion, let us give some considerations according to the calculation of the seismic effect of the underground concentrated explosions, and first of all, the vibration velocity of the particles of the soil, since its value serves as the criterion of danger for structures. The need for generalities is due to the fact that not all dynamic characteristics of waves are studied to a sufficient degree.

1. The calculation or the estimates of seismic danger for structures ougnt to be produced on every wave individually. In many instances based on the geological structure of the section, the explosive force and distance of the protected object can be predicted, as to which of the waves will have the maximum vibration velocity.

2. In the majority of cases the greatest danger for structures is Rayleigh's surface wave. Invariably the boundary of the danger zone in a seismic ratio determines the maximum speeds in this wave. They are determined according to displacements (9) and periods (10). The horizontal component is calculated according to the ratio $\frac{a_R^x}{a_R^z}$ whose values are given in Table 2.

3. The vibration velocity in the longitudinal wave one to be taken into consideration at close distances to the center of the charge, where it is usually predominant in intensity. The calculation of the parameters of waves are made according to formulas (11) and (12). The estimations of the vibration velocity in this wave can be made according to formula

$$u = 700\left(\frac{q^{1/3}}{r}\right)^2,$$

where r - hypocentral distance.

One ought to remember that in porous soils this formula gives high results. The depth of the charge when $h_3 < r_{\text{упр}}$ can be calculated by a graphic representation (see Fig. 22) for a surface wave; when $h_3 \geq r_{\text{упр}}$ one ought to compensate with $\alpha_p = 1.4$. The angle of departure of the longitudinal wave on the surface and a greater approach angle to a sunken foundation or underground structure are virtually difficult to determine; therefore, value u_p^z, which is by value close to a full velocity vector, can affect the structure both along the vertical and horizontal components, depending on ground conditions and the type of structures.

4. At all the investigated sites the speeds in wave N were either commensurable with wave velocities p and R, or less than them; therefore, during their calculations it is not possible to take them into consideration. Of course, for the full estimations the study of the dynamic characteristics of this wave is required.

5. The longitudinal wave, reflected beyond the critical angle p" can present considerable danger for structures. This wave appears in the presence of a sharp interface at a specific depth. So, at a site composed of loess deposits, wave p" in intensity is commensurable with the surface wave (see Fig. 14), whereupon in loess deposits due to its considerable porosity in comparison with the majority of the soils the intensity of the longitudinal wave can be on an order less. Consequently, in such soils as clay, mantling rock outcrops, the vibration velocities in wave p" can considerably exceed the velocity of the remaining waves, and constitute a threat to structures even at very great distances. The observations during explosions in loess deposits show that the factors which strongly affect the intensity of wave p", are the ratio of the explosive force to the thickness of the layer, and also the placement depth of the charge. Thus, the intense wave p" in comparison with other waves was obtained during the explosion of a 160 kg charge at a depth of 15-22 mm. During the explosions

of charge of the same force at shallow depths and a 10 t charge at a depth of 15 m, the intensity of wave p" is very small. The observed cases of intense vibrations at considerable distances when conducting industrial explosions compels one to focus his attention on the study of the dynamic characteristics of longitudinal waves reflected beyond the critical angle.

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